THE GREAT COURSES®

Understanding the Marvels of Medieval Technology

Course Guidebook

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Technological Development in the Middle Ages

This course explores a wide array of technological marvels—from tapestries to trebuchets, from plows to printing presses, from looms to longships, and from clocks to cathedrals—that were developed during the medieval millennium from roughly AD 500 to 1500. Although the geographic focus will be primarily on medieval Europe, there will be many opportunities to discuss important technological achievements that originated elsewhere—such as those that came from the Islamic world and the Far East—and then strongly influenced technological development in the West. This lecture begins the journey by examining a rather obscure piece of military architecture—the barbican gate—and provides an overview of the organization and scope of the rest of the course.

The Barbican Gate

- During the Norman invasion of Ireland—launched in 1171—Henry II, the king of England, granted a loyal Anglo-Norman knight named Hugh de Lacy the Irish kingdom of Meath, with the caveat that de Lacy would have to conquer it first. De Lacy set about the task by building a wooden ringwork castle just outside the village of Trim. The structure was burned by an attacking Irish army in 1174, but over the next 3 decades, de Lacy and his successors rebuilt the castle in stone. The resulting structure was the largest Norman castle in Ireland, and much of it remains intact.

- Today, visitors to Trim Castle will notice a square tower that projects from the main wall and is connected to it with an arched passageway. This odd feature is called a barbican gate—and when it was added to Trim Castle in the 1190s, it was the first use of this innovative military technology in Ireland.

From the outside, the barbican gate at Trim Castle appeared relatively innocuous, but the inside revealed a multilayered defensive system designed to make the entryway all but impregnable.

- If members of an attacking force were to storm the gate in an attempt to seize Trim Castle, they would need to first batter down the gate of the wooden palisade. But by that time, the Norman defenders would have dropped the temporary bridge that provides access to the elevated gateway.

- The attackers could use scaling ladders to reach the gateway—but they would come under fire from archers shooting down at them from above. In the meantime, the defenders would have closed and barred the heavy wood-and-iron door. If the attackers were to breach the door, they'd find that an interior trapdoor had been opened—and anyone who attempted to cross the open pit would be pelted with heavy stones or boiling water, dropped through an overhead opening called a murder hole.

    1. Any surviving members of the attacking force would discover that the arched side walls of the barbican actually enclosed a drawbridge that spanned a water-filled moat and could be raised quickly by an overhead windlass—presenting yet another stout barrier to entry.

2 Beyond the drawbridge, the interior passageway was protected not only by a heavy wood-and-iron grating called a portcullis—which was lowered from above—but also by two more doors and by murder holes in the vaulting above.

At the time of the barbican gate's construction, none of its technological components were new inventions. However, the gate's design adapted and synthesized the components in a way that made the system greater than the sum of its parts and fulfilled one of the key principles of fortification design: integrated defense in depth.

Trim Castle

Organization and Scope of the Course

- This course is an engineering course, not a history course. The focus will be on specific representative examples of medieval "technological marvels," with emphasis on how they were designed and built as well as how they worked. Relevant historical background will be considered only to the extent that it facilitates understanding the context from which these technologies emerged and the subsequent influences they had on medieval society.

- Each lecture addresses a particular type of technology that falls into one of the following five broad, thematic categories:
  - enabling technologies—such as in agriculture, textile manufacturing, ironmaking, and power production—that provided the food, raw materials, and energy on which the medieval economy (and more advanced technologies) depended;
  - military technologies, such as armor, weapons, fortifications, and siegecraft;
  - civil and structural engineering achievements, such as roads, bridges, and buildings of all kinds;
  - mechanical systems, such as industrial machinery, clocks, the printing press, and ships; and
  - surprising legacies of medieval technological marvels in the modern world.
- The term *technology* refers to any device, structure, system, or process that's created by humans to meet a need. For this course, a technology qualifies as a marvel if it meets either of two criteria:
  - its design or construction was particularly effective from an engineering perspective, or
  - its implementation had important social, political, or economic influences on the subsequent course of events.
- The beginning and end of the medieval era are the subject of much scholarly disagreement. In a general sense, the term *Middle Ages* refers to the historical period between classical antiquity and the early modern period. However, this definition isn't particularly helpful because the boundaries between the three eras are notoriously fuzzy. Similarly, defining these boundaries in terms of discrete historical events doesn't work very well for a more general study of the Middle Ages because no

single event can account for the full range of social, political, economic, and technological changes that distinguish the medieval era from the earlier and later periods.

- This course defines the Middle Ages as the period from roughly 500 to 1500. Scholars typically subdivide this period into the early Middle Ages, from 500 to around 1000; the High Middle Ages, from 1000 to around 1300; and the late Middle Ages, from 1300 to 1500—with the important caveat that the transitions between these periods were more gradual and less well-defined than these discrete numbers would suggest. The remainder of this lecture offers some historical context for the major technologies that are covered in the course.

The Early Middle Ages

- In the year 500, Europe was dominated by Germanic tribes that had begun migrating into the western Roman Empire 2 centuries earlier. These tribes eventually formed autonomous kingdoms that superseded Roman imperial rule.

- From a technological perspective, the demise of the Roman imperial bureaucracy was accompanied by a near-total loss of the engineering expertise required to design, build, and maintain large-scale infrastructure systems, such as aqueducts and road networks. Thus, during the Middle Ages, most of these great Roman engineered works fell into ruin.

- Yet, at the local level, there was far more technological continuity than scholars once thought. Important classical-era technologies—such as the warp-weighted loom for weaving cloth, the bloomery furnace for smelting metals, and the water-powered mill for grinding grain—remained in use through the early Middle Ages and would serve as enabling technologies for future technological development. In the 6th century, a little-used Roman-era agricultural implement—the heavy plow—would prove to be ideally suited for the soils of northern Europe, and its widespread use would contribute to substantial increases in agricultural production.

- Meanwhile, the eastern half of the Roman Empire—today called the Byzantine Empire—succeeded in fending off barbarian incursions and then initiated an ambitious (but ultimately unsuccessful) military campaign to regain control over the empire's former western provinces. During one campaign, while defending the city of Rome against an Ostrogothic siege, Byzantine engineers developed an ingenious floating water-powered mill and used it to prevent the city's population from starving. In Constantinople (the imperial capital), Emperor Justinian created an extraordinary architectural legacy—exemplified by the church of Hagia Sophia, completed in 537 and destined to remain the world's largest cathedral for another 1000 years.

- The 7th century was dominated by the astonishing military conquests of the Arabs—nomadic warriors who embraced the newly established Islamic faith and set out from the Arabian Peninsula to conquer the Near East, North Africa, most of the Iberian Peninsula, and a portion of southern France for Islam.

The Arab conquests are significant to this course, in that Islamic civilization became a great incubator for science and technology, while its extensive trade connections with China served as a conduit for the spread of technological knowledge from east to west.

- The principal interface between Islamic civilization and Christian Europe was Al-Andalus, the former Visigothic kingdom of Spain. In Al-Andalus, a unique spirit of religious tolerance engendered a peaceful coexistence and cultural fusion between Muslims, Jews, and Christians for more than 7 centuries.

- In northern Europe, the 8th century was dominated by the rise of the Frankish Carolingian dynasty, which reached its zenith when Charlemagne unified most of continental Western Europe north of the Pyrenees and was crowned emperor of the Romans by the pope in the year 800. In his court at Aachen, Charlemagne gathered scholars from throughout Europe and fostered significant advances in literature, writing, the arts, and law.

The imperial coronation of Charlemagne

- But by the mid-9th century, much of the previous century's progress was lost, as the Carolingian empire broke apart in a series of civil wars and the successor Frankish kingdoms were subjected to increasingly destructive invasions by Vikings from the north, Muslims from the south, and Magyars from the east.

- In the 10th century, continental Europe's defenses against these raids stiffened as the Magyars were defeated and the Franks cut a deal with a Viking chieftain named Rollo. In exchange for the region of northwestern France known today as Normandy, Rollo agreed that he and his warriors would settle down, convert to Christianity, and assist the Franks in defending against future Viking raids. Through this pact, Rollo's Christianized Vikings (or Northmen) became the Normans—the most indomitable warriors of the medieval era.

The military success of the Vikings was attributable, in part, to their superbly designed longships, which could sail on open seas and shallow rivers with equal finesse.

The High Middle Ages

- The 11th century saw the dawn of a long period of robust growth in economic activity, industry, trade, and prosperity. At the heart of this great Commercial Revolution was population growth of more than 200% between the years 1000 and 1300. This growth was enabled by substantially increased agricultural production, resulting primarily from three factors: first, the systematic conversion of forests and marshes into farmland; second, a series of technological improvements in plowing, land management, and crop rotation; and third, a change in the climate called the medieval warm period, which lasted from roughly 950 until 1300 and caused longer growing seasons and milder winters throughout northern Europe.

- As agricultural production increased, the need to grind ever-greater quantities of grain into flour stimulated steady improvements in water-powered and wind-powered systems, which became more mechanically efficient and were adapted to a wider range of topographic conditions.

- As Europe's population grew, so did its cities and towns, which became thriving hubs for the production of textiles, pottery, leather goods, and many other commodities. Textile production, in particular, was greatly enhanced through technological innovation—most notably, the introduction of the counterbalance treadle loom in the 12th century and the spinning wheel in the 13th century.

- During this era, architecture and structural engineering also flourished, with the development of sophisticated stone castles, innovative bridges, great monasteries, and grand cathedrals. Initially, these cathedrals were built in the Romanesque style, but by 1300, monumental Gothic cathedrals graced many European cities.

- Medieval Europe was also beset by near-continuous warfare. The most common form of conflict involved the siege—the process of gaining entry into an enemy fortification, often through the use of specially built machines such as the mobile siege tower, the battering ram, and the counterweight trebuchet—which was introduced into Europe in the 12th century and quickly became the dominant artillery weapon of the era.

The Late Middle Ages

- Starting in 1315, a series of cold winters and wet summers caused crop failures and widespread starvation. In 1337, the Hundred Years' War between England and France began, and starting in 1347, the Black Death rampaged across Europe and ultimately killed between one-third and one-half of the population.

Black Death

- Despite these depredations, this era saw some of history's most consequential technological advances. The invention of the mechanical clock fundamentally changed humans' perceptions of time. The blast furnace greatly increased the availability of iron tools, plowshares, horseshoes, and fasteners.

- Mechanical devices such as the crank and pushrod substantially expanded the range of industrial applications that could be powered by water or wind. New oceangoing ships—exemplified by the square-rigged carrack—enabled the age of discovery. And most importantly, the printing press stimulated an information revolution that literally changed the world.

- On the battlefields of the Hundred Years' War, the English longbow and the crossbow contributed to the growing obsolescence of the mounted knight. And by 1500, mobile gunpowder artillery had rendered stone castles entirely obsolete and stimulated the development of a fundamentally new approach to fortification design, called *trace italienne*.

- This period also coincided with the dawn of the Italian Renaissance—an era in which a unique community of artist-engineers brought new energy and a new conceptual approach to the development of technology.

The story of medieval technological development is only rarely one of revolutionary inventions; more often, it's a story about discerning value in the technological ideas of others and then adapting and improving upon these ideas to achieve a higher level of performance or to satisfy ever-more-demanding needs.

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2

Advances in Agricultural Technology

Lynn Townsend White Jr. is widely regarded as the 20th century's most influential historian of medieval technology. His 1962 book *Medieval Technology and Social Change* is a series of essays, each of which makes a bold claim about the influence of technological development upon medieval society. In White's essay on agricultural technology, which serves as the basis for this lecture, he claimed that a series of four technological innovations brought about an early medieval agricultural revolution and that the resulting increase in food production fueled the surge in population, growth of cities, expansion of commerce, and flourishing of culture that characterized the High Middle Ages. This lecture examines those four innovations—the heavy plow, the open-field system of land management, three-field crop rotation, and the horse collar—and the institutional contexts within which they developed. In the decades since the publication of White's book, his work has attracted at least as many critics as it has adherents, and this lecture will consider some of the criticisms as well.

The Early Medieval Manor

- In the late Roman Empire, most agricultural production occurred on large estates called latifundia, which were owned by aristocrats, manned primarily by slaves, and engaged in the production of agricultural products for sale. During the early Middle Ages, the latifundium evolved into a fundamentally different type of institution—the manor, which probably emerged during the decline of the Carolingian empire in the 9th century.

In modern terms, the latifundium was the agribusiness of the ancient world.

- Like the latifundium, the manor was an estate managed by an aristocrat—called the lord of the manor. However, the lord didn't own the manor; he was granted the right to hold the land by the king or a higher-level lord in exchange for military service and an oath of loyalty. This hierarchical system is called feudalism.

Medieval European city

- The manor's agricultural production was intended primarily to provide self-sufficiency for its inhabitants, rather than products for sale. And the work was performed by tenant farmers, who earned the right to use their land by paying rent or providing labor services to the lord. Although the tenant farmers didn't own the land they worked, they could keep much of the food they produced.

- The typical manor was organized into cultivated land, common pasture for grazing, and often a woodland, which supplied timber and firewood and provided hunting grounds for the lord. The manor's arable land was subdivided into many long, narrow strips—called selions. The demesne was the portion of the manor that produced crops directly for the lord, using labor services provided by the peasants. The other selions were the tenant holdings and were cultivated by the peasants for their own subsistence.

The Heavy Plow

- The long and narrow design of the selions is directly related to the heavy plow—the first of Lynn White's four influential agricultural technologies. To understand the significance of this invention, one must first understand the technology it replaced. Throughout the ancient Mediterranean world, the standard implement used to prepare soil for planting was the scratch plow, also called the ard. It consisted of a heavy beam, which was hitched to two draft animals (usually oxen), and the plow itself, which consisted of a wooden handle (the stilt) and a pointed iron plowshare fitted to its lower end.

- The plowman guided the ard by grasping the stilt with one hand while using a long, pointed pole (an oxgoad) to keep the animals moving forward. As the ard was pulled forward, it scratched a shallow furrow through the soil. Subsequent passes of the plow left a narrow strip of undisturbed soil between the furrows, so farmers had to plow each field a second time, in the perpendicular direction—a practice called cross-plowing.

- While effective for thin, dry soils, the ard proved inadequate for the heavy, wet, clay-rich alluvial soils of northern Europe. In response to this challenge, the heavy plow, or carruca, came into widespread use. A version of the implement was first used in China in the 1st or 2nd century, and some form of heavy plow probably saw limited use in the Roman Empire. But the carruca wasn't used extensively in Europe until the 6th century, when it was adopted in Slavic lands and then spread westward.

- The medieval carruca consisted of the following components:

    - a heavy wooden frame that incorporated a hitch for the draft animals, a pair of stilts, and a horizontal element (the sole);

    - an iron blade (the coulter) that sliced vertically through the sod as the plow moved forward; and

    - a chisel-shaped iron plowshare that cut horizontally through the soil and then lifted the soil and sod onto a curved wooden sidepiece (the moldboard), which turned the soil over and deposited it along the right-hand side of the plow.

The turning action of the heavy plow's moldboard was highly beneficial because it aerated the soil, controlled weed growth, and brought nutrients up to the surface while also burying the previous year's crop residue and any manure that was deposited on the field when it was used for grazing.

- After completing a pass, the plow had to be shifted laterally to the other side of the previously plowed ground so that the new soil lifted during the next pass would be deposited onto the previously plowed furrow.

- Use of the carruca had three important ramifications:

    - The heavy plow pulverized the soil so thoroughly with a single pass that cross-plowing wasn't needed anymore.

    - Because the process of turning a team of eight oxen at the end of each furrow was extremely cumbersome, the selions were made long and narrow to minimize the number of turnarounds. In medieval measurements, a typical selion was 1 furlong (660 feet) in length by 4 rods (66 feet) in width—the area of land that could be plowed by one ox-drawn plow in one day. This area is also exactly 1 acre (43,560 square feet). So today, when people describe the size of a parcel of land in acres, they're invoking the legacy of the medieval ox-drawn heavy plow.

Plowing a paddy field with oxen

- The process of plowing in clockwise circuits caused a net transfer of soil inward—from the edges of the selion toward the centerline. Over time, the flat ground was gradually transformed into a distinct ridge-and-valley topography, with the ridges corresponding to the centerlines of the selions and the valleys corresponding to the outer edges. This topography, which is still evident today in many European farm fields, proved to be quite beneficial because it was self-correcting in excessively wet or dry weather conditions and allowed crops with different water demands to be grown in the same field.

The Open-Field System

- From antiquity through the early Middle Ages, farmers used two-field crop rotation to avoid growing the same crop in the same field year after year, which depletes nutrients from the soil and reduces crop yields. A parcel of land was divided into two fields, and in any given year, one field was cultivated while the other was left fallow to recover the soil's fertility. The cultivated field and fallow field were alternated annually.

- On a medieval manor, individual peasant landholders held at least one selion in each field, so they could harvest a crop every year. But because the fallow field was also used as common grazing land for all the manor's livestock, the individual selions couldn't be fenced in—hence, the name open-field system. In this system, the peasants managed shared resources themselves and developed elaborate systems for allocating plows and teams, resolving disputes, and managing grazing land.

- The open-field system was inherently inefficient because farmers had to travel long distances between their widely scattered selions. Some scholars have claimed that communal regulation of agricultural practices stifled innovation and individual initiative—which could explain why, by the late Middle Ages, many 1-acre selions were being consolidated into large, enclosed, privately owned fields.

The Three-Field System of Crop Rotation

- Around the late 8th century, farmers began experimenting with a three-field system. A typical example might include one field planted in the fall with wheat, barley, or rye; one field planted the following spring with legumes—peas, beans, and lentils—and sometimes with oats for horse feed; and the third field left fallow and used for grazing. These crops were rotated annually so that each field could recover its fertility for 1 year of every 3.

- Three-field rotation was advantageous in many ways. The greater diversity of crops decreased the likelihood of famine if any one crop failed. Cultivation of legumes restored nitrogen to the soil and thus helped preserve its fertility. Cultivation of oats supported the increased use of horses for both agriculture and transportation. And, most importantly, three-field rotation increased agricultural production by placing 33% more land under cultivation in any given year.
- However, recent research suggests that the actual overall productivity increase was considerably less than 33%—simply because the three-field system wasn't as widely adopted as once believed. Evidence shows that this system, which placed greater demands on the soil, could be adopted successfully only in regions with very fertile soil—typically alluvial lowlands. In upland regions with thin or stony soils, this system often wasn't feasible.

The Horse Collar

- The horse collar was used to hitch a cart, wagon, or plow to a horse. It was probably developed in China in the 5th century and was introduced into Europe around 800, when it began replacing a different type of harness that had been used by the ancient Romans.
- In the early 1900s, a retired French cavalry officer named Richard Lefebvre des Noëttes conducted a research project that provided a seemingly definitive answer to why the horse collar replaced the old Roman-era harness. Lefebvre fabricated a replica of a Roman harness, which he called the throat-girth harness, and then placed it on a horse and tested the animal's capacity to pull heavy loads. The design of the harness was such that one strap passed across the horse's windpipe and restricted the animal's breathing. Lefebvre's experiments led him to conclude that the ancient Romans used oxen rather than horses to pull heavy loads.
- Based on Lefebvre's conclusion, later scholars theorized that the medieval horse collar solved the harness's design problem because the collar was configured to bear on a horse's shoulders—not its windpipe—enabling the horse to pull four to five times more load than if it were fitted with the

ancient harness. Thus, the invention of the horse collar made it possible for medieval farmers to use horses for plowing; and because horses are faster and have more endurance than oxen, their use substantially increased agricultural productivity.

Earliest depiction of the horse collar

- Lefebvre's research didn't attract much attention until it was cited by White—first in a 1940 journal paper and then in his 1962 book *Medieval Technology and Social Change*. No doubt because of White's stature as a scholar, the theory of the horse collar's revolutionary contribution to agricultural productivity was widely embraced—and has persisted to the present day, even though it's almost certainly wrong!

- In the 1970s, a French scholar named Jean Spruytte definitively refuted the theory by demonstrating that Lefebvre had based the design of his throat-girth harness on a flawed analysis of the ancient sources. Spruytte showed that, when fitted with a properly configured ancient harness—called a dorsal-yoke harness—a horse's pulling capacity is essentially equal to that of a horse equipped with a medieval horse collar. Thus, the horse collar wasn't the revolutionary technology that White claimed it to be.

However, the horse collar did allow for a lower point of attachment to the animal, which allowed the plow to be pulled more efficiently than if it were attached to the top of the animal's back. And evidently, this modest advantage led to a gradual increase in the use of horses for plowing, though oxen were still widely used on European farms well into the 17th century.

The picture painted by White is correct in its broad strokes, if not in every detail. Technology-driven agricultural progress was an important enabler of the vibrant, multifaceted civilization of the High Middle Ages.

Medieval horses in commission

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3

Textile Technology: From Twill to Tapestry

Of all the technologies explored in this course, none illustrate the nature of medieval technological development more effectively than the machines and processes developed for producing textiles. Recognizing subtle limitations in the well-established textile technologies from the ancient world, medieval artisans devised incremental improvements to address them. By the 15th century, the cumulative effect of those changes was an integrated series of highly refined machines for spinning, weaving, and finishing textiles on a scale that was previously unimaginable. The thriving textile centers that emerged as a result were among the most important economic engines driving the Commercial Revolution of the High Middle Ages. Because wool was the most common textile, this lecture focuses primarily on the production of woven wool cloth.

Traditional Spinning Processes

- Every wool textile began with a sheep that was sheared to produce a bundle of raw wool fibers called fleece. Dirty and contaminated with foreign material, raw fleece needed to be washed and combed before it could be spun into thread.
- The combed wool was drawn into a rope of loose, parallel fibers, called roving. This material was typically wound onto a wooden rod—called a distaff—which provided the spinner with a large supply of wool fiber close at hand.
- The traditional tool for spinning fiber into thread was the drop spindle—a wooden rod with a weighted disk (called a whorl) mounted near the bottom. After attaching a bit of fiber from the roving to the spindle, the spinner would spin the spindle to twist the fibers.

Woman with spindle whorl

- The spinner would then draft the wool—or draw out just enough fiber to constitute thread of the desired size—and use her fingers to guide the twisted thread up into the drafted fiber. By spinning and drafting continuously, the spinner produced a strong, uniform thread. When the spindle neared the floor, the newly spun thread would be wound onto the spindle so that spinning could resume.


Traditional wool spinning

Traditional Weaving Process

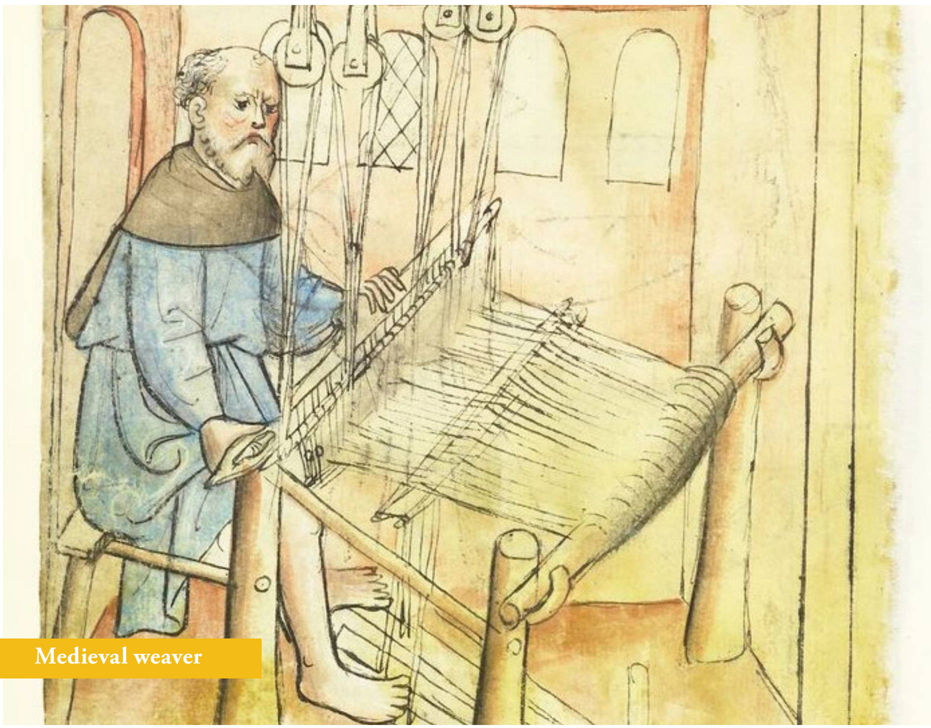
- Thread is transformed into cloth through the process of weaving—in which two perpendicular sets of threads are interlaced with each other. The vertical threads are called the warp, and the horizontal threads are called the weft.

- Weaving usually takes place on a loom, which essentially is a frame that holds the warp threads in tension while the weft thread is interwoven through the warp. Each pass of the weft thread through the warp is called a pick, and when each pick repeatedly passes over one warp thread and then under the next, the resulting cloth is said to be plain-woven.

- Twill-woven cloth is created by passing each pick over or under multiple warp threads. For example, in a 1/3 twill weave, each pick passes over 1 warp thread and then under 3, then over 1 and under 3, and so on.

Twill cloth is stronger than plain-woven cloth because the floating weft threads can be compacted more tightly and thus can produce cloth with more threads per inch.

- While weavers could use simple frame looms to make cloth by manually interlacing each pick through the warp, this technique had two limitations:
    - The resulting piece of cloth couldn't be any larger than the frame.
    - The loom was entirely impractical for using fine thread to create tightly woven cloth.


Medieval weaver

The Warp-Weighted Loom

- The limitations of the simple frame loom were effectively addressed in the vertical warp-weighted loom—which was invented in antiquity but remained in common use throughout the Middle Ages.

- This type of loom got its name from weights that kept the warp in tension. The warp threads were longer than the height of the loom, and the excess length was stored in bundles at the bottom. As weaving progressed, the newly woven fabric would be wound upward onto a rotating rod at the top, and then a corresponding length of additional warp would be unbundled at the bottom. This process allowed the length of the woven cloth to exceed the height of the loom.

- The most important feature of the loom was its mechanism for interlacing the weft through the warp. Half the warp threads hung vertically in the rear, while the others extended forward and were draped across a horizontal bar near the bottom of the loom. This subdivision of the warp created a triangular opening, called a shed.

- The rear warp threads were individually tied to a movable bar. The ties were called heddles, and the bar was called the heddle rod. When the weaver repositioned the rod, it pulled the rear warp threads to the front—a process called changing the shed.

- To begin weaving, the weaver would place a pick by passing a bundle of weft thread through the shed. Next, they'd reposition the heddle rod forward—thus changing the shed and locking the previous pick into the woven cloth. Before proceeding, the previous pick had to be locked into its final position by beating it upward with a wooden tool called a weaving sword. The weaver would repeat this process, starting from the opposite direction.

- Despite its improvements over the simple frame loom, the vertical warp-weighted loom still had five significant technological limitations:

    1. The weaver had to stand while operating the loom and thus would experience fatigue after weaving for a few hours.

2 Setting up and manipulating the bundles of excess warp threads could be quite cumbersome.

3 The width of the loom—and thus the width of the woven cloth—was limited to the distance the weaver could pass the weft thread from one hand to the other through the shed.

4 The heddle mechanism could be used to make only plain-woven cloth.

5 The need to manually manipulate the heddle rod and weaving sword after each pick interrupted the weaver's workflow.

The Counterbalance Treadle Loom

- By the 11th century, the cumulative effect of incremental adaptations to the warp-weighted loom amounted to a dramatic transformation in weaving technology, from a simple device to a sophisticated mechanical system that could produce a wide variety of high-quality textiles with significantly improved efficiency.

- The counterbalance treadle loom's design addressed the five key limitations of the vertical warp-weighted loom in several ways:

1 The orientation was changed from vertical to horizontal, which allowed the weaver to sit and also allowed for a longer machine.

2 The warp weights and bundles of excess thread were replaced by a second rotating beam, which kept the warp in tension and supplied additional thread more conveniently.

3 The weft thread now deployed from a long, boat-shaped device called a shuttle, which could be tossed from hand to hand to allow the production of significantly wider cloth.

4 The single heddle rod was replaced by four shafts, on which the heddles were mounted. The use of multiple shafts made it possible to produce both plain-woven cloth and a variety of twills.

5 The weaving sword was replaced with a beater—a pivoting comb-like frame used both to control the spacing of the warp threads and to beat each new pick into position in the woven cloth.

- This loom got its name from features related to the shafts, which were suspended from a harness consisting of pulleys, ropes, and small horizontal beams. The harness was actuated by foot pedals—called treadles—which improved the workflow by freeing up the weaver's hands from the repetitive repositioning of the shafts.

- The configuration of the harness was designed to convert a downward push (stepping on a treadle) into an upward pull (lifting a shaft). The required effort was minimized because each shaft was counterbalanced by the other shaft suspended from the same beam, and each pair of shafts was counterbalanced by the other pair suspended from the pulley. Through this mechanism, the weaver could lift any shaft—or any pair of shafts—by stepping on one or more treadles.

The Spinning Wheel

- As the counterbalance treadle loom came into widespread use during the High Middle Ages, weavers encountered a new challenge—the traditional process of spinning with a drop spindle simply couldn't produce enough thread to keep up with the looms' higher production rate. Thus, the stage was set for a new technological advance—the spinning wheel, which was invented in the Far East and found its way to Europe by the late 13th century.

- The first-generation medieval spinning wheel mimicked the manual spinning process. The spindle was functionally identical to a drop spindle, except that it rotated on a horizontal axis. The whorl doubled as a pulley, which was connected to the large drive wheel by a loop of string that served as a belt drive. Because the wheel was much larger than the pulley, a slow turn of the wheel caused rapid rotation of the spindle. The drive wheel also functioned as a flywheel—in the sense that once it was in motion, its momentum would keep it rotating at a steady rate.

- From an engineering perspective, the first-generation spinning wheel was a revolutionary invention—possibly the first use of a belt drive and flywheel as an integrated system. But from a practical perspective, it had much less impact on medieval textile production than one might guess. Once a spinner had spun an arm's length of thread, they needed to pause and wind the newly spun thread onto the spindle. These frequent discontinuities caused the finished product to be weaker and less uniform than hand-spun thread. Thus, many weavers were reluctant to use the thread.

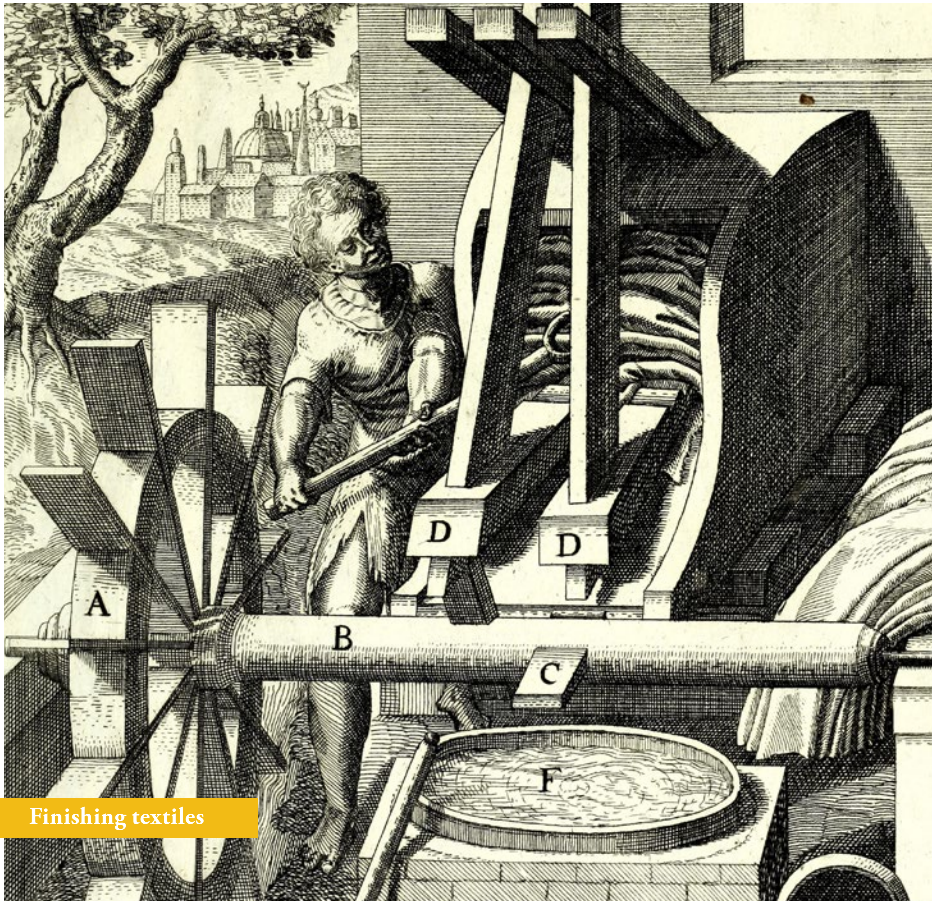
- In the 15th century, two important inventions were added to the spinning wheel. The first was the flyer spindle—a device that twisted thread and wound it onto the spindle simultaneously. But the spinner had to use both hands to operate the flyer spindle and therefore needed another way to turn the drive wheel. That issue was addressed with the second invention—treadle power. The use of a foot pedal to spin the drive wheel at a steady rate freed the spinner's hands to operate the spindle. From an engineering perspective, this mechanism is classified as a crank and pushrod—an extremely important invention.

Treadle power was the perfect complement to the flyer spindle—and their combined effect was to increase textile production by bringing spinning back into balance with weaving.

Finishing Processes

- Before the unfinished wool cloth could be made into consumer goods, two finishing processes—fulling and dyeing—were required. Fulling increased the thickness, compactness, and water resistance of wool cloth. Generally, the cloth was immersed in a cleaning fluid, then pounded to raise the wool fibers and allow them to interlock with each other. When the material dried, shrinkage further increased its compactness and strength.

- In antiquity, the cleaning fluid was typically human urine—a convenient, if unpleasant, source of ammonia. But in the Middle Ages, a naturally occurring claylike material called fuller's earth was also found to be effective for absorbing oil and dirt.



Finishing textiles

- The pounding action was accomplished by people walking on the immersed cloth or beating it with clubs. But in the early 11th century, the first water-powered fulling mills went into operation, giving textile production another major technological boost.

- Dyes were made exclusively from natural substances. Some were common and cheap, such as woad, a perennial herb used to make blue dye; others were exotic and expensive, such as kermes—a red dye made from an insect species of the same name.

While cloth could be dyed after being woven, the preferred practice was to dye the wool before weaving because the resulting color was truer and less likely to fade. Today, people use the phrase *dyed in the wool* to characterize beliefs that are ingrained and strongly held.

Tapestries

Steadily advancing technologies for spinning, weaving, and finishing found their ultimate expression in tapestry—an ancient artform that flourished in medieval Europe from the 13th century onward. A tapestry is a decorative handwoven textile that depicts a pattern or pictorial design and is typically used as a wall hanging. From a technical perspective, medieval tapestries had three principal characteristics:

- They were plain-woven textiles.
- They were weft-faced textiles—meaning that the warp threads were spaced relatively far apart so that the weft threads could be packed tightly together to conceal the warp entirely.

The Unicorn Crosses a Stream

- Because the weft was used to "paint the picture," those threads were discontinuous—meaning that each pick in a given color extended only to the boundary with the adjacent color, not across the full width of the textile.

To create a tapestry, the design was first prepared by an artist, who painted a full-size rendition, usually on canvas. This painting—called a cartoon—was then used as a guide by the weaver. Often, the cartoon was mounted directly on the loom, immediately behind the warp, so the weaver could replicate the colors and shapes accurately. Tapestries were woven with the back side facing the weaver—thus, the finished tapestry was always a mirror image of the cartoon.

The 11th-century Bayeux Tapestry—probably the most famous textile artifact that has survived from the Middle Ages—is not a tapestry at all! Its magnificent 230-foot-long depiction of the Norman Conquest of England is embroidered onto a plain linen background—not woven into the fabric itself, as a true tapestry would be.

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4

Metallurgy and Ironmaking

The Bayeux Tapestry is a magnificent 11th-century work of art featuring vivid, intricately embroidered depictions of the Norman Conquest of England. It also illustrates that iron was ubiquitous in the medieval world, as it appears in everything from the soldiers' armor to the castle builders' shovels to the ships' anchors to the farmer's plowshare. As this lecture shows, the production of inexpensive, high-quality iron was essential to nearly every other form of medieval technology.

Wrought Iron, Cast Iron, and Steel

- An alloy is a metallic substance formed by mixing a pure metal with one or more other elements. Wrought iron, cast iron, and steel are distinctly different (but closely related) alloys of iron and carbon; indeed, the only substantive difference between them is their carbon content. Wrought iron contains typically less than one-tenth of 1% carbon (by weight), making it nearly pure elemental iron. Cast iron has 2% or more carbon. And any iron-carbon alloy with carbon content between these two extremes is classified as steel.

- In general terms, increasing carbon content causes the alloy to get stronger but less ductile. Ductility is the capacity of a material to undergo large plastic deformations when it's loaded. When subjected to a large load, a ductile material will eventually break—but only after elongating substantially beyond its original length.

- Wrought iron is the weakest of the three alloys but also the most ductile. It bends quite easily with a light hammer stroke but also bends through a very large angle without breaking.

- Ductility allows wrought iron to be drawn into fine wire to make mail, hammered into thin sheets for plate armor, and forged into elaborately shaped objects that don't require high strength, such as stirrups. However, this ductility is entirely unsuitable for a sword or an ax-head because it's too weak and too soft to hold a sharp edge.

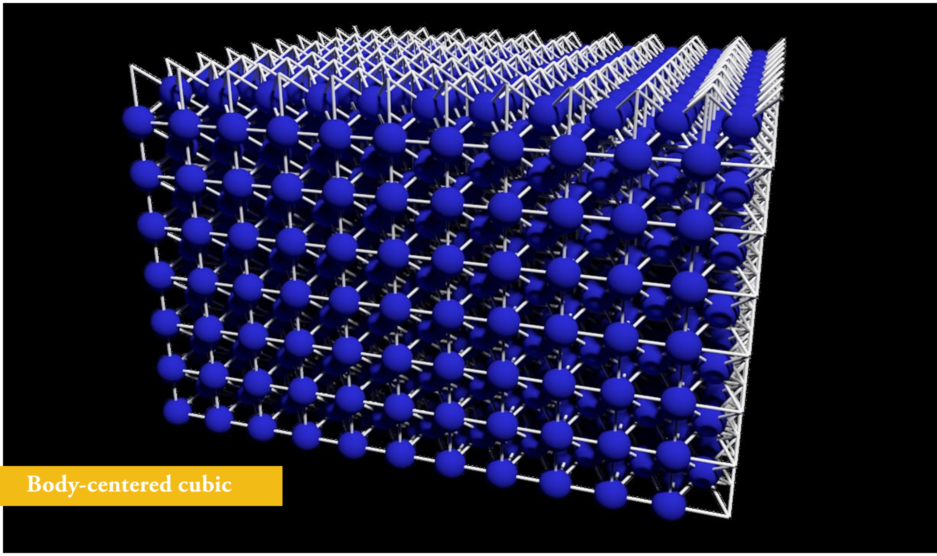
- Cast iron is many times stronger than wrought iron, but because of its high carbon content, cast iron is also extremely brittle—having essentially zero ductility—which limits its practical uses.

- Steel occupies the sweet spot between wrought iron and cast iron. It has just enough carbon to provide high strength but not so much that its ductility is compromised. However, relatively little steel was used in the Middle Ages because the process for making it was so complex and expensive that the metal was generally used only to fabricate specialized implements—like swords and cutting tools—for which its optimal properties were indispensable.

Increasing the carbon content of alloys results in more strength, less ductility, and a lower melting point. Pure iron melts at about 1500°C. The melting point of steel gradually decreases as its carbon content increases. And cast iron melts at about 1150°C.

Metallurgy

The individual atoms that constitute a metal are generally arranged in a geometrically regular structure called a crystal lattice—which for pure iron at room temperature consists of cube-shaped modules, each of which has one iron atom at each corner and another at the center of the cube. When this structure—called body-centered cubic—is replicated in all directions, it looks like this.



Body-centered cubic

Within this crystal lattice, the atoms are held together by metallic bonding. For the material to fail, the attractive force within the lattice must be overcome by an externally applied load. At the microscopic level, all ductile metals fail by shearing—meaning that an applied force causes one portion of the crystal lattice to slide with respect to another until the atomic bonds along the failure plane rupture.

Before the rupture, large plastic deformations occur. Whenever a molten metal solidifies, geometric imperfections—called dislocations—form throughout the crystal lattice. And when the metal is subjected to a load, these dislocations propagate through the lattice as bonds between atoms break and new bonds form until the dislocations have moved completely through the material. The aggregate effect of many dislocations moving in this way is a very large plastic deformation.

Dislocations move through a crystal lattice in essentially the same way as a wrinkle being pushed through a rug.

This phenomenon is affected by the addition of carbon, in that the carbon atoms block the movement of dislocations through the crystal lattice, resulting in higher strength and less ductility. Each disruption in the lattice also weakens the atomic bonds in its vicinity, resulting in a lower melting temperature. Therefore, the dramatic differences in the mechanical properties of wrought iron, steel, and cast iron are all caused by the subtle effects of a few carbon atoms on the crystal lattice of iron.

Smelting and the Catalan Furnace

Iron is quite plentiful in the earth's crust; however, nearly all of it is locked up in various mineral ores, such as magnetite and hematite. Magnetite is an iron oxide containing about 72% iron. To transform this mineral into metal, the iron must be extracted from the ore through a process called smelting.

From antiquity through the early Middle Ages, all smelting was performed in a simple furnace called a bloomery. The typical bloomery was constructed by digging a hole in the ground, lining it with stone or clay, and adding a clay pipe—called a tuyere—through which air could be blown. Forced air was supplied either by a bladder made from animal skin or by a set of hand-operated bellows.

- To smelt a batch of iron, the bloomery was filled with alternating layers of charcoal and ore; then, the charcoal was ignited, and the fire was intensified by a stream of air blown through the tuyere. Carbon from the charcoal combined with oxygen to form carbon monoxide gas—which then reacted with the iron ore, stripping away its oxygen atoms to form carbon dioxide and leaving behind pure iron.

- A fundamental technological limitation was that no ancient or medieval furnace could achieve the 1500°C melting temperature of pure iron. When iron ore is smelted at less than 1500°C, the product is a solid, spongy, white-hot mass called a bloom. The process also produces a liquid waste product called slag, consisting of unreacted ore, unburned charcoal, and other impurities. Some of this liquid flows to the bottom of the furnace—where it can be removed—but a lot of slag also fills the pores of the bloom itself. Thus, while the bloom is still white-hot, it must be removed from the furnace, placed on an anvil, and hammered vigorously to drive out the slag. The resulting material—wrought iron—gets its name from this final step in the bloomery process.

Iron bloom

The bloomery process could produce iron only in sequential batches, called heats. It took several hours to smelt a 50-pound bloom of iron, and then the furnace had to be cleaned out and recharged before the next heat could begin.

- A series of technological improvements to the bloomery process increased both the quantity and quality of the iron it could produce. One such improvement was the Catalan furnace, which was probably developed in the late 8th century in northern Spain.

- The heart of the Catalan furnace was a crucible—a square chamber lined with iron plates and set into a stout stone hearth. Within the crucible were two openings—one for removing liquid slag and one to accommodate a pyramid-shaped tuyere. The tall rear wall allowed ore and charcoal to be heaped above the hearth as the smelting operation progressed, and a shed roof and chimney allowed for operation in inclement weather. A continuous air blast was usually provided by two sets of bellows, opened and closed alternately by a counterweighted lever.

- The Catalan furnace could produce a bloom of 350 pounds per heat. Yet, the product of this process was still just wrought iron. To make iron strong and hard enough for swords and cutting tools, it needed more carbon.

Carburizing, Quenching, and Tempering

- To address the need for stronger and harder iron, ancient artisans developed a series of heat-treating processes that are still used today. The first—called carburization—was implemented by heating a piece of wrought iron over a charcoal fire for a long period of time at approximately 900°C. At this temperature, the iron's crystal lattice changes to a structure with more space between the iron atoms in the center of the cube; and in the carbon-rich environment of a charcoal-fueled furnace, some carbon atoms readily diffuse into this space.

- During carburization, the outer surface of the piece will absorb just enough carbon to transform the wrought iron into steel; and if it's then allowed to cool slowly—so that a well-ordered microstructure of iron and carbon can form—the resulting metal will be about three times stronger than wrought iron, while remaining reasonably ductile.
- The steel can be made even stronger by quenching it—that is, by removing the carburized metal from the furnace and immediately plunging it into cold water. Quenching effectively freezes the metal's microstructure such that dislocations can't move through this microstructure at all, so the resulting metal is extremely hard and approximately five times stronger than wrought iron.
- Quenched steel is also very brittle and thus isn't usable until it is tempered—which involves reheating the material to a moderate temperature and then allowing it to cool slowly in air. Quenched and tempered steel is suitable for a sword.

The Blast Furnace

- The blast furnace was the most important technological advance in medieval ironmaking. Although scholars are not certain how it was developed, there is solid archeological evidence of a very early blast furnace operating in Sweden sometime between 1150 and 1350; and starting in 1340, there are written references to German furnaces called *Flüssöfen* (flow ovens), which were almost certainly blast furnaces. But the technology didn't really proliferate until the late 14th century, when cast iron was found to be an ideal material for cannonballs and cast cannon barrels.
- The furnace itself was a stout stone tower—called the stack—about 20 feet tall. At the base of the stack was a small crucible, surmounted by a bottle-shaped chimney. A waterwheel drove two large bellows that provided a continuous blast of air through a tuyere into the crucible. The bellows were closed by cams mounted on the waterwheel shaft and then opened by counterweights.

- The stack was usually built into the side of a hill so that workers could charge the furnace by pushing their carts across a wooden bridge spanning from the hill to the top of the stack, then dumping successive layers of charcoal, iron ore, and limestone into the chimney.

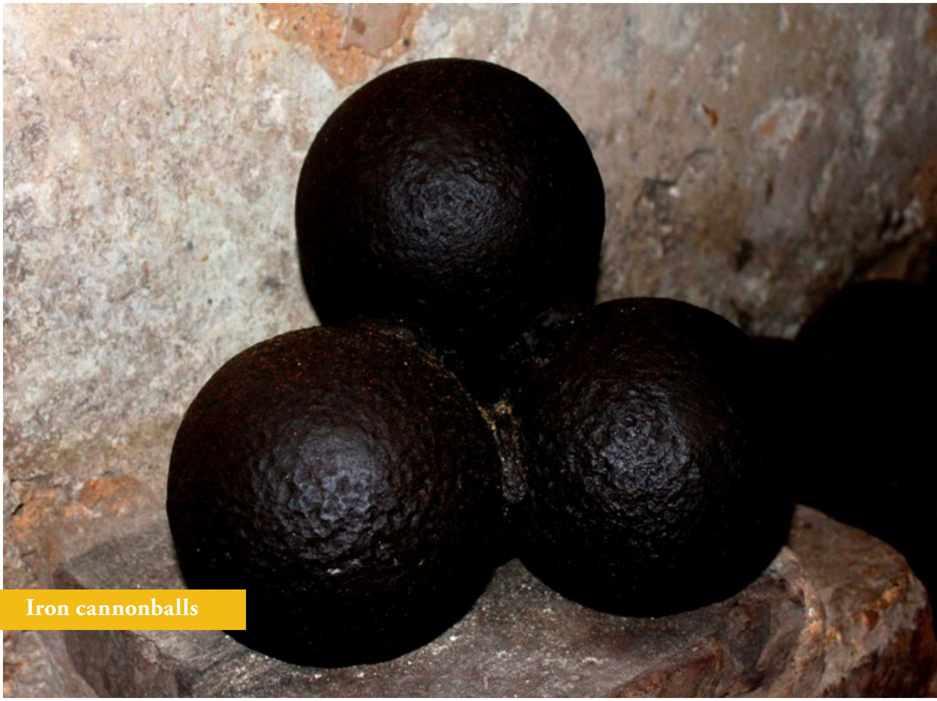
- Once the charcoal was ignited and the air blast initiated, the same chemical reactions that occurred in the bloomery began producing iron. However, because of its higher operating temperature, the blast furnace also dissolved about 4% carbon into the iron and then melted it, producing liquid cast iron. Meanwhile, the limestone served as a flux, reacting with impurities in the ore to create liquid slag. The molten iron and slag trickled down through the stack and pooled up on the hearth, where they were retained by a stone dam. When a sufficient amount of iron had accumulated, the slag was drawn off and discarded, and the iron was channeled into a series of shallow depressions in the sand-covered floor, where it hardened.

The shape of the depressions in the blast furnace's floor resembled a sow with her suckling piglets, so the resulting product was called pig iron—a name that is still used in steel manufacturing today.

- This new way of making iron had three major advantages over the traditional bloomery process. First, iron could be successfully smelted from low-grade ores that wouldn't have been usable in a bloomery. Second, the cast iron could be made into useful objects, such as church bells, simply by remelting it and pouring it into a mold. And most importantly, a blast furnace could be operated continuously for months on end, resulting in an enormous increase in productivity.

The Finery Process

- The blast furnace produced only cast iron, which was fine for bells and cannonballs but was too brittle for most other practical applications. Perhaps as early as the 13th century, ironmakers began using the finery process for converting cast iron into wrought iron. In general, this technology used a special furnace—called a finery—to remelt cast iron that had been previously smelted in a blast furnace.



Iron cannonballs

- A blast of air was then directed into this molten iron to reduce its carbon content—a process called decarburization, in which oxygen from the air blast combined with carbon in the cast iron to produce carbon dioxide and a large bloom of wrought iron that also contained a lot of slag. Heavy, water-driven trip-hammers were then used to drive out the slag and form the bloom into conveniently sized wrought iron bars. Later, when blacksmiths forged these bars into useful objects, they could still use heat-treating techniques like carburization, quenching, and tempering to further modify the properties of the metal.

- The transformation of the ironmaking process had profound effects at every level of medieval society, from warfare to commercial activity. And blacksmiths—who had previously worked primarily in the armories of the great lords—now established shops in villages and towns where they could better serve people's needs.

Blacksmiths became such vital members of their communities that Smith became one of the most common surnames in the English language.

Late 16th-century bell by Miles Graye

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5

Waterpower Systems

By the year 1500, waterpower was ubiquitous, and the technology had been transformed from a single-function machine used for milling grain to a versatile prime mover that could be used for practically any industrial application. Medieval waterpower systems took many different forms, depending on the water source, topography, and type of waterwheel. This lecture explores the science of waterpower and looks at several different waterwheel configurations used during the Middle Ages—including the horizontal, undershot, and overshot systems—and how they evolved in design and efficiency.

The Evolution of Waterpower Use

- The earliest unambiguous written references to water-powered mills are from the 1st century BC; however, many scholars believe the technology actually originated 2 centuries earlier—in the dynamic, scientifically rich culture of the eastern Mediterranean region. And recent archeological finds have demonstrated that by the 1st century AD, waterpower was being used extensively across the Roman world, though almost exclusively for milling grain.

- After the Western Roman Empire collapsed in the 5th century, the development of waterpower technology faltered but never died out completely. Mills continued to operate in some regions of Italy and southern France; from these pockets of technological continuity, waterpower again spread outward across Western Europe.

Barbegal—ruins of the Roman mill

Ever-increasing agricultural production stimulated ever-greater demand for milling. At the same time, medieval lords discovered that they could reap substantial profits by building water mills on their manors, forcing their peasants to use those mills, and charging exorbitant fees for the privilege of doing so. As a result, water-powered mills proliferated. In the 15th century, many mills were performing functions other than milling grain—such as fulling cloth, making paper, and driving the bellows at blast furnaces.

The Science of Waterpower

At the heart of every water-powered mill is a waterwheel—a device that extracts energy from a reservoir or flowing stream to produce mechanical power. During the Middle Ages, waterwheels were built in three distinctly different configurations—horizontal, undershot, and overshot—each with its own characteristic strengths and weaknesses.

Ancient wooden water mill

- If a waterwheel is supplied by a reservoir, then its source of power is the potential energy embodied in the elevated mass of water impounded in the reservoir. There are several ways to represent potential energy mathematically, but for phenomena involving fluid flow, it's convenient to use a vertical distance called head (h). Head is measured from the surface of the reservoir to the elevation at which the outflow makes contact with the wheel. A larger head corresponds to more potential energy.

- When the reservoir outlet is opened, the potential energy is converted into kinetic energy as water flows from the outlet, impacts the waterwheel with a velocity (v), and turns the wheel to produce mechanical power. In this context, kinetic energy can be calculated as the velocity squared divided by 2 times the acceleration of gravity (g), which is 32.2 feet per second squared:

$$\text{Kinetic energy} = v^2 / 2g$$

- According to the principle of conservation of energy, the potential energy of the reservoir and the kinetic energy of the water impacting the wheel are equal—meaning that the head (h) also equals v^2 divided by $2g$. When solving this equation for the velocity, the result is v equals the square root of $2gh$.

$$h = v^2 / 2g$$

$$v = \sqrt{2gh}$$

- A direct relationship exists between head and velocity of flow. For example, if a reservoir has 10 feet of head, the outflow will impact the waterwheel at approximately 25 feet per second. Furthermore, if the waterwheel is supplied by a stream flowing downhill, rather than a reservoir, the same mathematical relationship applies. If the stream is flowing at a velocity of 25 feet per second, it has the same potential to power a waterwheel as a reservoir with 10 feet of head—thus, the stream has 10 feet of head.

- The concept of head is vital to this lecture because the power input to a waterwheel from either a reservoir or a flowing stream is equal to h times W—where W is the weight of water supplied to the wheel per unit of time. For example, suppose the 10-foot-deep reservoir is supplying water to a wheel at a rate of 20 gallons per second. Water weighs about 8.3 pounds per gallon—so *W* is 166 pounds per second. Thus, the power input from the reservoir to the waterwheel is 1660 foot-pounds per second. In more familiar terms, 1 horsepower is defined as 550 foot-pounds per second; thus, the power input from the 10-foot reservoir is about 3 horsepower.

- The power output of a real-world waterwheel is always less than the power input—in part because all real-world machines experience energy losses due to friction and other factors, but also because two of the three medieval waterwheel configurations discussed in this lecture are fundamentally limited in their capacity to transform the energy of flowing water into the energy of a rotating shaft.

- The effectiveness of a waterwheel is typically expressed in terms of mechanical efficiency. In this context, mechanical efficiency is defined as the wheel's power output divided by the power input from the water source.

Mechanical efficiency = power output / power input

- For example, if a waterwheel is capable of producing 1 horsepower of output from the 3-horsepower input it receives from the reservoir, then its mechanical efficiency is 33%.

1 hp / 3 hp = 33% mechanical efficiency

Key Takeaways

The power available from a water source depends on two different factors—the available head and the quantity of flow—both of which are strongly dependent upon the site.

The relative importance of these two factors is different for the three different waterwheel configurations examined in this lecture. Thus, in the Middle Ages, the head and quantity of flow available at a mill site often dictated the type of wheel that could be built there.

The concept of mechanical efficiency provides a useful tool for comparing the effectiveness of the three different waterwheel configurations.

The Horizontal Waterwheel

- The simplest of the three medieval configurations was the horizontal waterwheel—so named because it spun in a horizontal plane. The wheel consisted of multiple radially oriented blades attached to a hub that drove a vertical shaft. The shaft extended upward through the floor of the miller's workspace, through a stationary bed stone, and into a runner, which was fixed to the shaft. The gap between the runner and bed stone could be adjusted by repositioning a heavy beam below, on which the waterwheel, shaft, and runner were supported. Grain was supplied by a wooden hopper, suspended above the runner.

- To operate the mill, the outlet opens, allowing a jet of water to flow from the reservoir through an inclined chute and onto the blades of the waterwheel. As the water strikes the waterwheel, it applies a force to each blade. This force causes torque—which is the tendency of a force to cause rotation about an axis. Mathematically, torque is equal to the magnitude of the force (F) multiplied by the perpendicular distance between the force and the axis (d).

$$\text{Torque} = F \times d$$

- Torque causes the waterwheel to rotate—with two important consequences. First, the waterwheel starts producing mechanical power, or power output—which can be calculated as torque multiplied by rotational speed. Second, the torque decreases as the rotational speed increases. This second phenomenon is like someone running with the wind at their back. The faster they run, the less they feel the wind because the difference between their speed and the windspeed is decreasing. In the same way, the rotating wheel "feels" less force from the water jet because the blades are moving in the same direction as the water.

- At max load, the waterwheel produces no power because it isn't rotating. At zero load, the waterwheel rotates rapidly; but because the torque is zero, the power output is also zero.

- In between max and zero load, the power curve rises to a peak and then falls; however, because of the inherent inefficiency in transferring energy from the water jet to the waterwheel blades, the peak power output,

Horizontal waterwheel

or mechanical efficiency, is only about 30% of the power input from the reservoir. In practice—because of the additional real-world energy losses due to friction, water turbulence, and such—medieval horizontal waterwheels could probably achieve only 5% to 15% efficiency.

The most important feature of the horizontal waterwheel was the mechanical simplicity that resulted from the direct connection between the wheel and the runner. But over time, these wheels were superseded by larger vertical waterwheels, in part because of the horizontal waterwheel's low efficiency.

The Undershot Waterwheel

By the High Middle Ages, the most common waterwheel configuration was the undershot wheel—a vertical waterwheel that rotated on a horizontal shaft and was driven by water flowing underneath the wheel and striking radially oriented vanes.

- The challenge with any vertical waterwheel is that its horizontal shaft can't drive the millstone directly, as the horizontal wheel could. Connecting the wheel shaft to the runner shaft therefore required right-angle gearing.
- Such gearing typically used two types of gears. The cogwheel was a wooden disk with perpendicular wooden teeth, and the smaller lantern pinion used wooden or metal rods sandwiched between two disks. With the cogwheel mounted on the waterwheel shaft and the pinion on the runner shaft, rotation of the waterwheel caused the runner to spin.
- This system used two different-sized gears because the optimum rotational speed for milling grain is significantly higher than the speed of a typical waterwheel. Because the cogwheel is larger in diameter than the pinion, the pinion spins faster, and the runner's speed can be adjusted by changing the ratio of the two gear diameters.
- Compared with the horizontal waterwheel's mechanism, the right-angle gearing was more complex, but it also offered an important advantage—the ability to achieve an optimum milling speed regardless of the available stream velocity.
- To accommodate fluctuations in a river's water level, the undershot mill was almost always constructed in conjunction with a dam or other structure that could hold the water level steady and provide a controlled quantity of water to the wheel. A mechanical outlet mechanism—called a sluice gate—was integrated into the dam; when opened, it provided a controlled flow of water to the wheel through a channel called the headrace. The water then flowed back to the stream through another channel, called the tailrace.
- The waterwheel itself was positioned within a wheel pit that was just slightly wider than the vanes, so very little water could flow around them. This feature was important because it ensured that the entire flow was contributing to power production. The resulting benefit was that an undershot wheel could achieve significantly higher efficiency than a horizontal wheel—a theoretical maximum of 50% and a practical maximum of about 30%.

The Overshot Waterwheel

- The overshot wheel was similar to the undershot in its vertical orientation, horizontal shaft, and right-angle gearing, but it was fundamentally different in three ways. First, water was supplied to the top of the wheel by an elevated headrace. Second, the waterwheel's rim incorporated a series of buckets rather than radial vanes. And most important, the wheel was powered by gravity—that is, by the weight of water continuously filling the buckets on the downstream side of the wheel, thus creating the torque that rotated the wheel and generated power.

- Because it was gravity-driven, an overshot waterwheel required much less water than an undershot wheel. And because the entire flow was being captured in buckets, nearly all the power input from the reservoir was being transformed into power output. In other words, the theoretical efficiency of this wheel was 100%. In practice, it could probably achieve 70% efficiency, and so—all other things being equal—its power output would have been more than twice that of an undershot wheel.

- The great limitation of the overshot configuration was that the water had to be supplied to the wheel by an elevated headrace, and the water supply had to have a head that was at least equal to the diameter of the wheel. Consequently, medieval overshot mills were significantly more expensive than the alternatives and could only be used at certain sites. These constraints account for the greater popularity of the less-efficient undershot wheel.

Small-Stream Water Sources

- A mill located along a small stream would need much of the stream's normal flow to power the waterwheel. Thus, such waterpower installations normally used a dam to impound the entire flow and create a millpond.

- Constructed of earth, stone, timber, or some combination of these materials, the dam served four main functions. It provided a means of accommodating daily and seasonal variations in streamflow. It increased the head of the water source and held it constant. It controlled the water supply to the wheel, by means of one or more sluice gates. And it incorporated a spillway, which allowed the millpond to overflow whenever the inflow from the stream exceeded the required outflow to the mill.

For an undershot waterwheel, the headrace was usually a relatively short, artificial channel extending on a downhill slope from the dam to the wheel pit. The tailrace needed a relatively large gradient to ensure that spent water didn't back up into the pit and hinder the wheel's rotation. An overshot wheel was often positioned farther away from the dam, so the elevated headrace could attain the required height above ground level.

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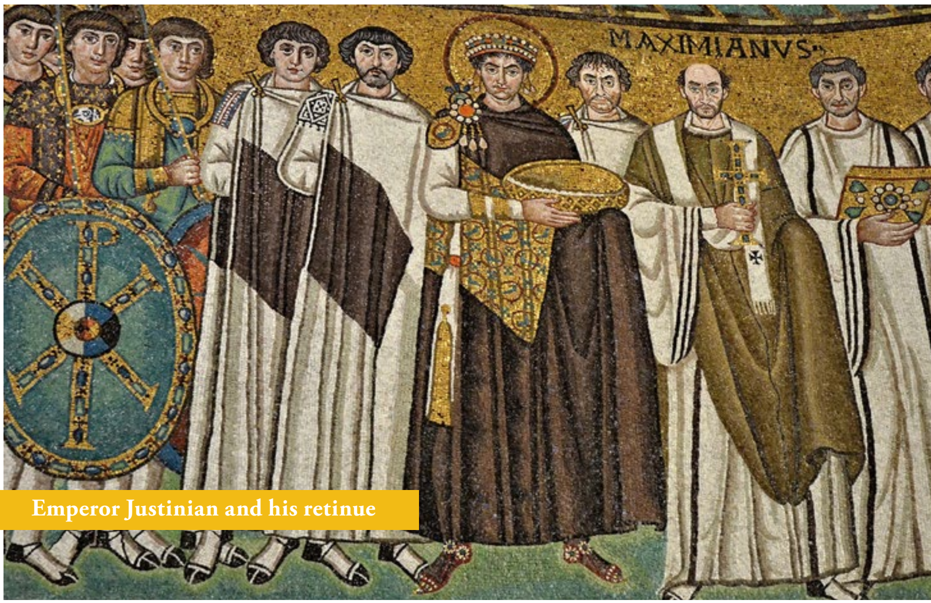
6

Boat Mills, Tidal Mills, and Windmills

In the early Middle Ages, most mills probably used small horizontal waterwheels that were well suited to the high-velocity, low-quantity flow provided by small, upland tributaries. As the demand for power grew, larger vertical waterwheels became more prevalent; however, because these wheels required more water, they had to be sited on larger streams. Eventually, the increased urbanization of the High Middle Ages demanded more milled grain in major population centers—most of which were located along large rivers, where constructing water mills was inherently problematic because of the variable water level and the relatively slow current along the riverbanks. This lecture looks at several ways medieval millwrights addressed these challenges.

Boat Mills

In the year 535, the Byzantine emperor, Justinian I, launched a war against the Ostrogothic kingdom of Italy as part of his ongoing campaign to reclaim the Western Roman Empire, which had fallen during the previous century. Justinian's general, Belisarius, landed in Sicily with 7500 troops and quickly conquered the island. The following spring, he crossed over to the Italian mainland, and by December 536, Belisarius occupied Rome. Yet, within 3 months, he and his troops were besieged within the city by a larger Ostrogothic army. To force a Byzantine surrender, the Goths cut off Rome's water supply, provoking a food supply crisis as water-powered mills that ground most of the city's grain stopped working.



Emperor Justinian and his retinue

The Byzantine engineers turned to the Tiber River and built a fleet of boat mills to generate power for grinding Rome's grain. Each mill consisted of two interconnected pontoons supporting a large undershot waterwheel that drove two sets of millstones through right-angle gearing. These mills were moored to the shoreline but could be positioned farther out in the channel, where the current was stronger. And because they rose and fell with the river, their operation wasn't affected by variability in the water level. Through this ingenious expedient, Belisarius was able to feed the city's population, withstand the Gothic siege, and provide later medieval millwrights with one solution to a growing challenge—the need to build water-powered mills in regions that were geographically ill-suited for waterpower.

- Boat mills were built in increasing numbers from the 6th century onward. By the 12th century, floating mills were a common sight in most European cities.

Bridge Mills, Dams, and Tidal Mills

- Over time, millers learned that they could maximize power production by positioning their rigs at a narrow point or island in the river channel—where the resulting constriction in the flow would cause the water to speed up. This insight probably led to the innovation of the bridge mill, which first appeared in the 12th century in Al-Andalus, then quickly spread to northern Europe.

- The configurations of medieval bridge mills varied considerably, but they all had a common feature: They were positioned within (or just downstream from) the opening between two bridge piers to take advantage of the faster current caused by the constricted flow.

- Over time, as medieval engineers gained proficiency in dam construction, a few cities—such as Toulouse, in modern-day France, and Chester, England—were able to build dams across major rivers to control the water supply to their mills. However, such installations hindered navigation and were costly to build, so large dams weren't feasible in most places.

- The most daunting challenge was developing waterpower in low-lying coastal regions, where rivers were too broad to be bridged or dammed and too slow to generate power without some means of raising the water's head. One clever response to this challenge was the tidal mill, which was in widespread use by the 12th century but was probably invented earlier.

- The typical tidal mill was powered by a conventional undershot waterwheel located adjacent to a dam constructed across a coastal inlet or bay. At low tide, the waterwheel was idle. As the tide came in, the inward flow caused a gate in the dam to swing open; but as the tide peaked and then ebbed, the outward water pressure held the gate shut, thus impounding the tidewater on the landside of the dam. Finally, when the tide had receded, a sluice gate was opened, and the impounded water was routed beneath the waterwheel to produce power. This system worked well, but its power output was inherently limited because it could only operate during a portion of each tidal cycle.

Windmills

- Unlike many of the technologies discussed in this course, the windmill was a bona fide medieval invention. The earliest "true" windmill was the panemone, developed in Persia sometime during the 8th or 9th century.

Medieval windmill

- The panemone consisted of a rotor with radial vanes mounted on a vertical axle. Because the vanes rotated in a horizontal plane, this machine is categorized as a horizontal windmill—an inherently inefficient configuration because the wind can only drive half of the vanes at any given time. The remaining vanes must be shielded, or the rotor won't turn at all. And because it sat in a fixed enclosure, the panemone could be operated only when the wind was blowing within a relatively narrow range of directions.

- The vertical windmill first appeared in Europe in the late 12th century. It's possible that it was inspired by the Persian panemone; however, there's no clear evidence of wind power technology migrating westward. And because the two configurations are so radically different in conception, it's more likely that the vertical windmill was invented independently.

Today, people associate windmills with Holland; however, the device was probably invented in England and then spread eastward, across the Low Countries, northern France, and northern Germany—regions where waterpower was often infeasible, either because there were few fast-moving streams or because the usable streams froze in the winter.

Post-Mills

- The vertical windmill underwent two major stages of development. The first was the post-mill—whose defining characteristic was that the rotor and mill enclosure were mounted on a stout vertical post, such that the entire rotor could be turned to face the wind. This configuration ensured that all its vanes could take the wind simultaneously and that the mill could operate regardless of the wind direction.

- The vanes were called sails, and like the sails on a ship, they were made of cloth supported on heavy timber masts (called stocks) and spread across a wooden lattice—the equivalent of a ship's yardarms. To maximize the rotor's rotational speed, the canvas was unfurled and spread across the entire framework; to reduce the speed, it was partially or fully furled.

- Because the sail was angled, wind that struck it from the front was deflected downward. Newton's third law says that for every action, there's an equal and opposite reaction; thus, as the sail exerted a force on the air to deflect it downward, the air exerted an equal and opposite force on the sail, causing the torque that spun the rotor. And the slight twist in the sail allowed the full length of the sail to contribute to the generation of torque—optimizing the rotor's mechanical efficiency.

Nutley windmill

- Inside the post-mill was the rotor's axle—called the windshaft—which was tilted slightly backward, such that the rotor's plane of rotation wasn't perfectly vertical. This angled orientation had a subtle aerodynamic advantage over the vertical orientation.

- Mechanical power was transmitted from the windshaft to the mill's machinery through two wooden gears. The larger one (called the brake wheel) drove a smaller pinion—the wallower—which rotated the vertical spindle that was fixed to the upper millstone (or runner).

- A hopper for raw grain was mounted above the runner. The millstones were enclosed within a casing that captured the milled flour and routed it through a chute into a lower room, where the flour was bagged and stored.

- The defining feature of the post-mill was its ability to pivot, so the rotor could always be faced into the wind. To facilitate the rotation, a heavy wooden boom—called the tailpole—was integrated into the structural frame of the mill enclosure. The tailpole also counterbalanced the weight of the rotor and supported a stairway that provided access to the mill.

- Medieval post-mills pivoted on a rather crude bearing that would have generated a lot of frictional resistance; thus, they could only be turned by animal power or by mechanically amplified human power. The latter was achieved through the use of a windlass, which was operated by looping a rope around its shaft, anchoring the rope to two posts, and then turning a ship's wheel—another example of repurposed nautical technology. Each pound of force applied to the wheel was magnified by about 500%.

- To control the rotor speed while it was spinning in a strong wind, first, the rotor had to be stopped using the braking system, which demonstrated mechanical ingenuity at its best. Then, with one pair of sails positioned vertically, the miller climbed the sail's wooden framework like a ladder, furling the sailcloth and tying it down as needed.

The post-mill is widely regarded as the medieval era's most original contribution to power production technology.

Tower Mills

- Because the mill enclosure had to be capable of rotating, the post-mill was fundamentally limited in size and weight. Thus, its potential power output was similarly limited. And because it had to be light enough to rotate, the structure was vulnerable to overturning during extreme windstorms.

- The tower mill addressed both of these limitations. It was probably developed in the late 13th century but didn't spread widely across Europe until the 15th century. Its only rotating component was a small, timber-framed cap, in which the windshaft was mounted. The body of the mill was a fixed tower, usually made of brick or stone.

- The tower mill's configuration was a major improvement over the post-mill because the robust masonry tower could be built much taller and was significantly more resistant to overturning. The taller tower could carry larger sails and could take advantage of higher windspeeds aloft. Thus, this system could produce more power while also providing more interior space.

- Over the centuries, the tower mill underwent continuous refinement and ultimately attained an impressive level of technological sophistication. In the fully developed system, the only mechanical components mounted within the rotating cap were the windshaft and the brake wheel. The wallower, powershaft, millstones, hoist, and all associated gearing were mounted within the masonry tower.

- The key technological innovation that made this configuration possible was a series of iron rollers, mounted within the upper rim of the tower. The rollers allowed the cap to rotate without a central pivot, so the wallower and powershaft could be positioned directly on the cap's axis of rotation. Thus, when the cap was turned, the teeth of the brake wheel and wallower remained engaged.

- Because of their large size, tower mills generally incorporated at least two sets of millstones, which required a new type of gearing—a large spur gear driving multiple pinions—to transmit power from the main powershaft to the spindles. The hoist also received its power from the main shaft through right-angle gearing.

- Tower mills were substantially more expensive than the simpler post-mills and, as a result, accounted for only about 25% of the wind power produced during the Middle Ages.

The Dutch *Wipmolen*

- The *wipmolen* was an elegant compromise between the post-mill and tower mill. It was developed by the Dutch in the early 1400s in response to a highly specialized need—draining wetlands in conjunction with large-scale land reclamation in the region known today as the Netherlands.

- The type of pump developed was called a scoop wheel. It was essentially an undershot waterwheel, operated in reverse. As the scoop wheel rotated within its tightly fitted wheel pit, its vanes pushed water from the lower level to the higher level, and a hinged door prevented the water from flowing back into the pit.

Booterlotse mill

- Like the post-mill, everything above the *wipmolen*'s brick foundation was made entirely of wood; thus, the structure was relatively light and could be built on soft ground. Its rotating upper enclosure was mounted on a vertical post, supported within a robust, pyramidal tower. But unlike the post-mill, the *wipmolen* used a hollow post, thus allowing a centrally positioned powershaft to extend from the wallower, downward through the post, and into the fixed foundation, where the shaft drove the scoop wheel through right-angle gearing. And because the wallower was centrally positioned, only the windshaft and brake wheel needed to be mounted in the rotating cap—just as in a tower mill.

Raising water to the significantly higher elevations needed for land reclamation required multiple windmills operating in series—with the first mill raising water from the marsh to an intermediate-level basin, successive mills raising the water to higher-level basins, and the last one emptying it into a canal or river. Through this brilliantly engineered system, medieval engineers wrested vast expanses of arable land from the North Sea.

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7

Mounted Shock Combat: The Knight's Panoply

From a broad historical perspective, the Battle of the Lake of Antioch was a relatively insignificant event during the First Crusade. But this minor battle serves as a near-perfect example of the medieval knight in action—fighting as heavy cavalry and engaging in a uniquely effective form of warfare that Lynn White termed mounted shock combat. The knight's panoply—his horse, armor, weapons, and equipment—can be viewed as a highly effective technological system that performed three principal functions: protection, mobility, and the employment of offensive weapons. This lecture examines the panoply of a typical 11th-century Norman knight.

The Battle of the Lake of Antioch

- In February 1098, the First Crusade was teetering on the brink of disaster. Having reached their next objective—the Turkish-held city of Antioch in northern Syria—the badly depleted Crusader army learned that a 12,000-man Turkish relief army was advancing toward them. The Crusaders sent a small force of 700 mounted knights to attack the advancing column—a force roughly 15 times larger—while the rest of their army remained at Antioch.

- On the night of February 8, the knights, led by the Norman prince Bohemond, took up a position on high ground overlooking a bridge that the Turks would have to cross as they approached Antioch. The next morning, as the Turkish column came into view, the Crusaders charged. Caught off guard, the Turks fell back in disarray but then regrouped and fought back fiercely. The Crusaders withdrew to a narrow strip of land between the Orontes River and the Lake of Antioch—thereby drawing the Turks onto ground that effectively negated their numerical advantage. From this position, Bohemond led a final charge that broke the will of the Turkish army and sent them retreating.

Battle of Antioch

- The typical 11th-century Norman knight—the iconic armored warrior who fought alongside Bohemond at the Lake of Antioch—was a member of the nobility; only landed aristocrats could afford the horses, armor, and weapons required to fight as heavy cavalry. Each knight was also a vassal to a lord, fulfilling his obligation to provide military service in exchange for a grant of land—the fundamental transaction at the heart of feudalism.

- The Normans were the undisputed masters of mounted shock combat, which was just coming of age in the 11th century. Scholars know a lot about the arms and armor used by these Normans thanks to the Bayeux Tapestry, which provides a richly detailed depiction of the Battle of Hastings in 1066—just 3 decades prior to Bohemond's victory at Antioch.

Protection: The Helmet, Shield, and Armor

- The simple iron helmet worn by an 11th-century Norman was essentially unchanged from the one worn by his Viking ancestors 2 centuries earlier. Called the nasal helmet, it was composed of the skull and noseguard. The skull could be forged from a single sheet of iron or assembled from riveted iron bands and plates. Its conical shape was designed to deflect blows to the head. The noseguard helped protect the warrior's face without obstructing his vision.

- The iconic Norman kite shield was developed for cavalry but was adopted by many infantry formations as well. The shield's wide, curved top protected the knight's shoulders and torso, while its long, pointed lower end covered his left leg.

- The shield was constructed of a light but resilient wood, then covered with cloth or animal hide and reinforced with a central iron boss. It was often equipped with heavy leather straps—called enarmes—which allowed the knight to hold the shield securely while fighting or to carry it on his forearm while keeping his left hand free—for example, to hold his horse's reins.

- From the Carolingian era through the 13th century, most knights rode into battle wearing a simple hauberk—a tunic composed entirely of iron mail. The garment sometimes included an integral hood, which protected the knight's head and neck; otherwise, a separate mail or leather hood—called a coif—was worn instead.

- Mail was invented in antiquity and used extensively throughout the Middle Ages. It was composed entirely of small, interconnected iron rings—each held closed by a tiny rivet. Mail was extremely flexible, and it provided good protection against sword cuts and—to a lesser extent—sword thrusts. However, mail could be easily penetrated by arrows, and it offered no protection against blunt-impact weapons.

Chain mail

- An important invention that facilitated the fabrication of mail was the drawplate, which was used to create fine iron wire by heating a larger-diameter rod or wire and then pulling it through successively smaller holes in the plate until the wire reached the desired diameter.

- To make mail, the iron wire would be heated in a furnace and then inserted into a small hole in a device called a mandrel. A crank was then turned to wind the wire onto the shaft. The wire coil was then removed from the shaft, and a wire cutter was used to create individual rings. Next, the iron rings were annealed—a process of heating and cooling that relieved the internal stresses caused by bending the wire.

- Both ends of each ring would be flattened with a hammer and punch. Then, the two flattened ends would be overlapped, and a smaller-diameter punch would be used to drive a rivet hole through the overlap.

- Most medieval mail was assembled in a 4-in-1 pattern—so called because each individual ring was linked to its four surrounding rings. The interconnection was made permanent by adding a rivet—a short length of the same wire that was inserted through the punched holes in the ring and then flattened with pliers.

A medieval hauberk typically used 20,000 to 30,000 rings.

Weapons: The Sword and Lance

- All medieval swords had two main components—the blade and the hilt. The central groove of the blade—called a fuller—lightened the blade without significantly reducing its strength or stiffness.

- The hilt had three components:

  - the cross guard, which protected the knight's hand and prevented it from sliding forward onto the blade;

  - the grip, a wooden core wrapped with leather; and

  - the pommel, which helped balance the sword while also locking the knight's hand onto the grip.

- As a technological entity, the sword represented the pinnacle of medieval metallurgy. Its blade had to be strong and stiff, tough enough to take a sharp impact without shattering, and hard enough to hold an edge. And because the wrought iron produced by the bloomery process (discussed in lecture 4) was too soft to be used for edged weapons, medieval bladesmiths used a variety of techniques to meet the demands.

- One approach was the piled steel blade. To fabricate this type of blade, carburized steel bars were stacked, heated in a furnace, and then hammered vigorously to fuse the laminations into a single bar—a process called forge welding. Through this process, thin layers of steel are uniformly distributed throughout the thickness of the piece, thus greatly improving the overall strength and stiffness of the metal. The outer surface of the blade could then be further hardened by quenching and tempering.

A process called pattern-welding was used to create the finest Viking and Anglo-Saxon swords during the early Middle Ages. The smith used two different types of iron bars to produce a composite with the desirable qualities of both constituents. After assembling an alternating stack of these bars, the smith forge welded them together and then gave it a few twists. Finally, after grinding and etching the surface of the composite forging, an intricate geometric pattern was revealed.

- The knight's primary weapon when fighting as a heavy cavalryman was the lance—a long wooden shaft with a socketed iron head.

- The weapon carried by the Norman knights at Hastings wasn't a true lance, in the sense that it was relatively light and could be used in three distinctly different modes, each of which was normally associated with a different type of weapon. In the depictions on the Bayeux Tapestry, knights are most often shown with this weapon raised overhead, in an overhand grip—a position from which they could either throw it like a javelin or thrust it downward like a spear. But in a few cases, knights are shown charging with the weapon couched—that is, tucked beneath the right arm and held in an underhand grip—the tactical employment usually associated with a true lance.

- When this weapon was used as a javelin or spear, its power depended primarily on the force generated by the knight's arm and shoulder muscles. But a couched lance mobilized the entire mass of the charging horse, the knight, and all his equipment, and at the instant of impact with a

Knight charging with couched lance

target, this immense momentum was transformed into an impulsive force, concentrated at the tip of the lance. This force is the "shock" in White's term *mounted shock combat*.

- As its effectiveness became better understood, charging with a couched lance became the standard cavalry tactic. In the mid-12th century, the lance was optimized for this operational mode by making it longer and heavier. With this development, the weapon could no longer be used as a javelin or spear—and the primacy of mounted shock combat was fully realized.

Mobility: Horse Saddles and Stirrups

- When fighting as heavy cavalry, knights used large, powerful war-horses—called destriers—that were specially bred for the task. The interface between the horse and rider was provided by two of the medieval era's most important military technologies—the high-cantle saddle and stirrups.

- The saddle design incorporated a raised pommel up front and a high cantle in the back, which greatly improved the knight's stability. The high cantle was essential for the charge with a couched lance because it ensured that the knight wasn't unhorsed by the impact of the lance with its target.
- The saddle consisted of an underlying wooden structure—called a tree—that was padded with wool or horsehair and covered in leather. Held firmly in position by one or two girth straps and a breast strap, the tree was designed to distribute the knight's weight broadly across the horse's back without applying pressure to the animal's spine. It also provided attachments for the era's most controversial piece of military technology—the stirrup.

Reconstruction of a Roman saddle

- The earliest unambiguous evidence of a true stirrup is from early 4th-century China, but precursors were probably being used in India at least 5 centuries earlier. In the late 6th or early 7th century, the technology was carried into eastern Europe by Central Asian invaders; and by the 8th century, stirrups were well established in the West.

- The controversy over the stirrup stems from White's 1962 book, *Medieval Technology and Social Change*, in which he claimed that the introduction of the stirrup into Western Europe had a "catalytic influence" on subsequent events—namely, the development of mounted shock combat as a uniquely effective form of warfare, the associated rise of a class of military elites who were the only members of European society who could mobilize the financial resources needed to engage in this form of combat, and the institution of feudalism as a means of obligating these elites to fight for their lords when called upon to do so.

- Many scholars have criticized White's thesis for oversimplification, selective use of evidence, and questionable connections between cause and effect. And while some of the criticisms are justified, one could argue that others derive from evidence that wasn't available in 1962, and some are simply unfair.

- However, White's claim that mounted shock combat would not have been possible without the stirrup is unequivocally true. Stirrups greatly enhanced a mounted warrior's lateral stability in the saddle and thus significantly enhanced his ability to fight from horseback. But it's equally important to recognize that mounted shock combat also wouldn't have been possible without the front-to-back stability provided by the high-cantle saddle or the focused power of the heavy lance or the flexible protection of the mail hauberk.

The key point of this lecture is that no single piece of "kit" can fully account for the 11th-century knight's effectiveness. He dominated the battlefield because his entire panoply functioned as an integrated technological system, in which the whole was greater than the sum of its parts. It was the knight's unique combination of mobility, protection, and weaponry that made shock combat possible.

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8

The Medieval Arms Race

Between the 11th and 14th centuries, medieval warfare saw many profound changes. Three of these changes were technological in nature. First, the development of plate armor provided men-at-arms with substantially improved protection. Second, this improved protection stimulated the development of weapons purposefully designed to defeat plate armor. And third, the longstanding dominance of heavy cavalry was increasingly threatened by infantry using pikes and other pole weapons and by archers using crossbows and longbows. This lecture explores the technologies associated with these trends.

Full Plate Armor

- During the 12th century, the term *knight* changed fundamentally when it became a social rank. From that point forward, heavily armored warriors who fought primarily from horseback were called men-at-arms rather than knights.

- From the Carolingian era through the 13th century, the most common type of armor was the hauberk, made entirely of iron mail. Early hauberks were short-sleeved and covered only the upper body; but over time, the coat and sleeves were lengthened, and separate mail coverings for the legs, hands, and head were added. However, men-at-arms remained vulnerable to concussion weapons, bowed weapons, and the lance.

- To address these vulnerabilities, armorers started adding supplemental steel plates to the hauberk. These plates were riveted to the inside of a leather or cloth garment, which was worn on top of a mail hauberk. The trend toward greater protection continued with the early 15th-century development of full plate armor, consisting of contoured steel plates strapped directly to the body rather than to a foundation garment.

Coat of plates

- A superb example of full plate armor was recovered from the ruins of a Venetian fortress that fell to the Ottoman Turks in 1470. A lower-leg covering—called a greave—was made of hinged halves that fully enclosed the calf and was secured with straps and buckles. A spaulder protected the shoulder while providing freedom of movement through the use of lames—overlapping strips of sheet metal, interconnected with rivets. Lames were also used to accommodate joint rotation at the feet and waist. Flanges were an important structural detail that greatly increased the strength and stiffness of the piece.

- The helmet was both an integral component of full plate armor and a fascinating case study in the evolution of military technology. One particularly interesting example—the hounskull bascinet—came into use around 1380 as an adaptation of the simpler 13th-century bascinet. Early bascinets were open-faced and closely fitted to the head because they were often worn underneath a great helm—the iconic barrel-shaped helmet of the High Middle Ages.

Great helm

- Men-at-arms would wear one helmet under another because the great helm provided superb protection but very poor visibility. So, a man-at-arms might wear it to advance against enemy archers and then remove it before engaging in a melee, where a wider field of vision was essential; the bascinet provided some degree of head protection after the great helm was removed.

- Eventually, soldiers of all types started wearing the bascinet as their sole helmet. But men-at-arms needed face protection, so a simple hinged visor was added, and this appendage eventually evolved into the distinctive conical beak of the hounskull bascinet. Its features were effective at deflecting blows, protecting the eyes, providing ventilation, and protecting the neck.

Plate armor was a well-engineered system that reflected not just the ingenuity and craftsmanship of the late medieval armorer but also improvements in three other areas of medieval technology:

Ironmaking: The blast furnace, finery forge, and associated enhancements in metallurgy made large-scale adoption of steel plate armor possible.
Waterpower: The bellows, forging hammers, rollers, and grinding wheels—which were powered by water—were essential to the armorer's craft.
Weapon design: Better armor stimulated better weaponry, which then prompted further improvements in armor—a developmental cycle that has been characterized as a medieval arms race.

The Evolution of the Sword

- As an offensive weapon, a sword can be used in two different modes: thrusting and slashing. During the early and High Middle Ages, increasingly effective mail armor made slashing attacks less effective, so swords had to be adapted for use in both modes. The optimum physical characteristics associated with each mode were quite different.

- With the advent of full plate armor in the early 15th century, slashing attacks became largely ineffective, and a fully armored opponent could only be defeated by thrusts precisely aimed at the gaps in his armor. Thus, swords designed solely for thrusting became common.

As bladesmiths optimized swords for the highly specialized tactic of attacking gaps in an opponent's armor, armorers responded by covering these gaps with supplemental plates over the knees, elbows, and armpits. And so, the arms race continued.

One facet of the medieval arms race can be seen in the evolution of the sword, which shows a gradual transition from the slashing configuration to the thrusting configuration—an evolution driven by concurrent improvements in armor.

The Pike

The pike was an ancient weapon that was revived in the 14th century to provide infantry with a means of fighting heavy cavalry. A long wooden shaft with a pointed steel head, the pike was strictly a thrusting weapon, and its only significant tactical advantage was its long reach. Thus, it was only effective when used by a large, dense formation, which could stop a cavalry charge with a wall of deadly spikes and then hold the horsemen at bay, outside the reach of their handheld weapons.

Pike square

- But dense formations of pikemen were also excellent targets for archers. Armies that used the pike successfully—most notably, the Swiss—mitigated this vulnerability by equipping their pikemen with substantial armor and integrating them with formations of crossbowmen and, later, hand gunners.

- During the late Middle Ages, other types of pole weapons proliferated. The most famous was the halberd, which incorporated a spike for thrusting, an ax blade for chopping, and a side spike that could be used to punch through armor or pull an opponent off his horse.

The halberd became so closely associated with Swiss armies that even today, it's carried by the Swiss Guard at the Vatican.

The Longbow

- The conventional handbow was a prehistoric invention that remained in use throughout the Middle Ages. The two basic types are the self-bow, made from a single piece of wood, and the composite bow, which was laminated from two or more materials. The 14th-century English longbow was a conventional self-bow in every sense, except for its great length—typically about 6 feet—and its tremendous power. To appreciate this marvel, it's helpful to understand the science behind its power.

- When any structural material is loaded, it experiences either tension (it elongates) or compression (it gets shorter). When a bow bends, its convex side—called the back of the bow—experiences tension, while the concave side—called the belly—experiences compression.

- Most English longbows were made of yew—a species of coniferous tree that produces wood with great strength and flexibility. The tree's heartwood (the material located at the center of a branch or trunk) is very strong in compression, while the sapwood (around the perimeter) is relatively stronger in tension. Thus, longbows were fabricated by cutting staves radially from a branch and carving them into shape with the heartwood oriented toward the belly and the sapwood toward the back.

- When the longbow is drawn, a force is applied through a distance, which has the effect of transferring energy into the system and storing it in the elastic bending of the bow. When the bowstring is released, most of the stored energy is transferred into the arrow as kinetic energy, which is a mathematical function of the arrow's mass and velocity. Therefore, for an arrow of a given mass, the more elastic energy that can be stored in the bending bow, the higher the arrow velocity will be.

- A force-draw curve is a graph that plots the pulling force versus the distance drawn. The point at the top of the curve represents the bow's two most important performance characteristics—its maximum pulling force, called the draw weight, and the corresponding draw length. The elastic energy stored in the bow turns out to be mathematically equal to the area underneath the curve. Thus, this area provides an effective way to visualize the bow's power.

- The maximum draw weight that a typical archer can apply repeatedly, under battlefield conditions, is roughly 100 pounds. And the maximum draw length is about 30 inches—a physical limitation imposed by the length of the archer's arms. The English longbow was so effective because its length, cross-section dimensions, and material properties resulted in a draw weight of roughly 100 pounds at a draw length of 30 inches. Thus, this weapon maximized the amount of elastic energy that a human archer could impart to a bow without mechanical assistance.

The Crossbow

- The crossbow, which was probably invented in ancient China, appeared in medieval Europe around the 10th century and then superseded the handbow in all European armies except England's by the 12th century.

- A typical first-generation medieval crossbow was composed of four main components:

    - a wooden stock—called the tiller—which had an iron stirrup lashed to its front end;

    - a wooden bow, called the lath;

- a stout bowstring, usually made of hemp; and
- a trigger mechanism.

The projectile—called a bolt or quarrel—consisted of a short wooden shaft, with two or three fins added for aerodynamic stability, and an iron head that was specifically designed to punch through armor.

The process of drawing a crossbow is called spanning. To span the weapon manually, the archer could place one foot into the stirrup and then pull the bowstring upward with both hands and engage it with the trigger mechanism. Once the bolt was loaded, it was ready to shoot.

Crossbow

Unlike the longbow, the crossbow didn't require any physical effort to hold it in the spanned configuration, so the archer could wait for the opportune moment, then take aim and pull the trigger. As a result, the crossbow was much easier to shoot accurately than a longbow.

The crossbow's trigger mechanism had one major drawback, in that the draw length was only about 5 inches. That meant that a crossbow with the same draw weight as the longbow (100 pounds) would have only 15% as much stored energy.

- Because of this inherent limitation, another ancient technology—the composite bow—was revived for crossbows around the end of the 12th century. A composite lath was fabricated by gluing laminations of horn and sinew—which are strong in compression and tension, respectively—to a wooden structural spine. These materials enabled the construction of heavy composite laths with 500- to 600-pound draw weights, which could approach the energy storage capacity of a longbow. But such crossbows couldn't be spanned manually, so a variety of mechanical devices were developed to assist with this task.
- Over time, the longbow would lose the medieval arms race because it required tremendous skill and physical fitness to operate effectively, and its simplicity offered few opportunities for technological improvement over time. In contrast, the crossbow could be operated effectively with minimal training, and it was well suited to long-term technological improvements.

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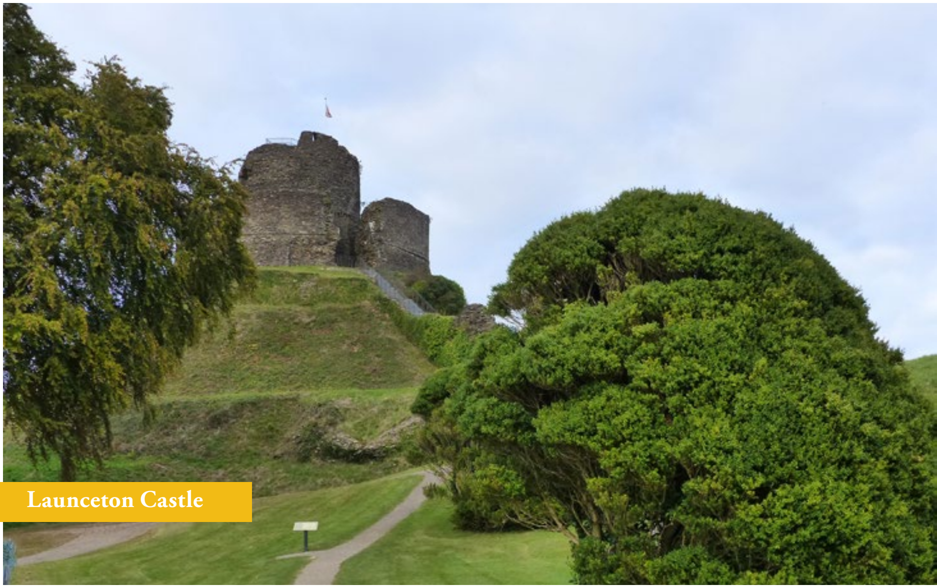
9

The Castle: A Story Written in Stone

Despite technological advances in medieval weaponry, armor, and equipment, feudal armies generally tried to avoid head-to-head clashes because a king or prince who lost a pitched battle might also lose many of his most loyal vassals. A more prudent way to gain control over territory and people was to build castles or seize the enemy's fortified places by conducting sieges. No two castles were alike. Each one represented a unique set of historical circumstances and topographic constraints—the influences of which were permanently enshrined in its walls, towers, and gateways. This lecture examines the castle as an engineered system.

The Various Roles of Castles

- By definition, a castle is the private fortified residence of a lord; yet, this simple description doesn't adequately capture the many ways that castles influenced medieval Europe.
- From a military perspective, the castle was used as a means of exerting control over a region, route, or waterway, which was done through the force of mounted men-at-arms stationed within. Thus, even though the castle's function was fundamentally defensive, its key military role was to provide a secure base for offensive operations in the surrounding region.
- From a political perspective, the castle was integral to feudalism because it often served as a venue for the lord's administrative and judicial functions, and it was typically garrisoned by the lord's vassals in fulfillment of their military service obligation. Lords could grant castles to faithful vassals, but castles also empowered faithless vassals to assert independence from their lords. Through these mechanisms, castles strongly influenced the political geography of medieval Europe.



Launceton Castle

- From the economic and social perspectives, the castle was integral to the manorial system, in that it provided protection for the lord's peasant workforce while also serving as a means of controlling them.

Motte-and-Bailey Castles

- European castle building began during the late 9th century, as the Carolingian empire was disintegrating and external threats from Viking, Magyar, and Muslim invaders were increasing. Responsibility for defense against these threats became increasingly localized, such that previously undefended towns surrounded themselves with walls, and nobles built castles from which they could defend their lands and laborers.

- Most of these early castles were rather crude structures—simple timber palisades or earth embankments, sometimes appended to the ruins of ancient Roman, Celtic, or Anglo-Saxon forts. But in the late 10th century, a more thoughtfully designed (and uniquely medieval) fortification called the motte-and-bailey castle appeared in northern France.

- The motte was a conical mound—sometimes a natural hill but usually a man-made embankment of soil excavated from the surrounding ditch. At the top of the motte was a timber palisade and a wooden building called the keep, which served as the lord's residence, a watchtower, and a citadel that commanded the entire site.

- The bailey was a larger ground-level enclosure, surrounded by a palisade atop an earthen rampart and a ditch that was sometimes filled with water to create a moat. The bailey contained barracks, stables, barns, workshops, and other facilities that supported the castle's economic activity. It was accessed by a fortified gateway and a bridge across the ditch.

- The motte-and-bailey castle was widely adopted in northern France during the 11th century, then introduced into England, Wales, and Ireland by the Normans, and it eventually spread to Germany and the Low Countries. Over time, many motte-and-bailey castles were strengthened by rebuilding their timber elements in stone.

William the Conqueror built roughly 500 motte-and-bailey castles during his conquest of England.

Cardiff Castle

Use of the motte-and-bailey castle declined sharply during the late 12th and 13th centuries for three reasons. First, significant advances in siegecraft drove the development of more robust defensive works. Second, during the Crusades, Westerners encountered superior Byzantine and Muslim fortifications and brought these ideas back to Europe. And third, advances in construction technology made robust stone structures increasingly feasible and prestigious.

Carrickfergus Castle: Phase 1

The new generation of stone castles that emerged in the 12th century represented a major technological advance over the motte-and-bailey. A good example is Carrickfergus Castle, located along the coast of Belfast

Lough in Northern Ireland. This castle—one of the best preserved of all Anglo-Norman castles—was constructed in four distinct phases between the late 12th century and early 14th century.

- In 1177—8 years after the Anglo-Norman invasion of Ireland began—a knight named John de Courcy led a small force into Ulster, with the goal of seizing more Irish territory. De Courcy recognized that the rocky peninsula of Carrickfergus was an ideal site for a castle from which to control overland travel and seaborne commerce along the coast.

- The structure built by de Courcy between 1177 and 1195 was, in effect, a motte-and-bailey castle reimagined in stone. It consisted of a massive rectangular keep and a bailey enclosed by a tall curtain wall. A ditch was excavated across the promontory to reinforce the castle's defenses against an overland attack from the north.

- The keep was a 4-story tower with walls ranging from 10 to 13 feet thick, surmounted by battlements and four watchtowers. Its ground floor was a vaulted cellar that originally housed a guardroom, storage areas, and a well—positioned directly over the spring that served as the castle's water source.

- The tower's sole entrance, on the first-floor level, was accessed by an external stairway. This floor was a public space that probably served as a waiting area for visitors. Access to the other floors was provided by a spiral staircase embedded within the southeastern corner of the keep.

- The second floor was a public space where the lord conducted administrative business and entertained his guests. And the uppermost floor served as his private residence.

- The curtain wall closely followed the promontory's western and southern shorelines but was set back from the eastern shoreline to accommodate a gateway. The castle's great hall—a venue for entertaining guests and holding communal meals—was built into the east wall.

- At the top of every curtain wall was a wall walk and battlement. The wall walk served as both a platform for the employment of weapons and a protected passageway for movement of troops along the wall. The battlement was normally crenellated, meaning that it was composed of alternating raised segments (called merlons) and lower segments (called crenels). Soldiers could stand behind the merlons for protection and then step to an opening formed by an adjacent crenel to fire their crossbows.

At Carrickfergus, de Courcy added a wooden palisade as part of an innovative defensive feature called a bent entrance—which required anyone entering the castle to cross a drawbridge and negotiate a long, narrow corridor before making a sharp turn to enter the gateway into the inner bailey. An enemy force attempting this route would fall under continuous fire from multiple directions.

Carrickfergus Castle

As the defensive system became more formidable, de Courcy also grew in power, prestige, and independence from the Crown. When this independence started looking like a threat, King John of England convinced one of his loyal subordinates, Hugh de Lacy, to attack and seize de Courcy's lands and castles. In 1204, de Lacy defeated de Courcy in battle, sent him into exile, and was rewarded the following year with Carrickfergus Castle and the title Earl of Ulster.

- But soon, de Lacy was also perceived as a threat to the Crown, and in 1210, King John personally led a siege against Carrickfergus. De Lacy was forced into exile, and Carrickfergus became a royal castle without a resident lord.

Carrickfergus Castle: Phase 2

- King John initiated Carrickfergus's second major phase of construction—the most important element of which was the replacement of the wooden palisade with a stout stone curtain wall and an enhanced main gateway and drawbridge on the north side.

- The most important technological enhancement of this construction phase was the addition of four towers, which were built integrally with the curtain wall—and thus are called mural towers. One of these towers protected the main gateway, and the others were positioned at key points along the curtain wall.

- Mural towers provided elevated platforms for the employment of projectile weapons. And because these towers usually projected forward from the curtain wall, archers could shoot parallel to the wall—and thus, engage enemy troops along the base of the wall. Mural towers were also often positioned at corners in a curtain wall to mitigate the inherent vulnerability of these corners to undermining and damage by artillery projectiles.

- To facilitate the employment of projectile weapons below the level of the battlements, most mural towers (and some curtain walls) also incorporated arrow loops—vertical slits through which archers could shoot. An arrow loop's opening, or embrasure, is narrow on the wall's outside face to protect the archer but wide on the inside to maximize the archer's field of fire.

- Both longbows and crossbows were used in the defense of castles, but crossbows were strongly preferred because they were better suited for use in confined spaces—and because the crossbowman's inherent vulnerability while reloading was effectively mitigated by the tower's well-protected fighting positions.

Carrickfergus Castle features a unique triple-loop crossbow position, which was incorporated into the design to defend against a seaborne attack from the east.

Carrickfergus Castle: Phase 3

- In 1216, King John died, and his son, Henry III, ascended to the throne. Eleven years later, the exiled Hugh de Lacy gained Henry's favor and was restored to the earldom of Ulster. Having also resumed his role as lord of Carrickfergus, de Lacy initiated the castle's third phase of construction, which continued until his death in 1242. This phase included a monumental gatehouse and new curtain walls that enlarged the castle's footprint to cover the entire peninsula.
- The gatehouse configuration—two round towers flanking a vaulted passageway—had been developed by the famous Anglo-Norman knight William Marshal for Chepstow Castle in the 1190s. It became a common feature of castles and fortified cities throughout the 13th century.
- At Carrickfergus, the gatehouse was particularly important because it formed the primary line of defense against an overland attack. The 3-story structure also housed an arms room, guardhouse, chapel, prison, and quarters for the constable—the official who commanded the castle's military garrison.

Carrickfergus Castle: Phase 4

- During the early 14th century, the resident lord—Richard de Burgh—made further enhancements to the gatehouse, including the addition of a drawbridge and portcullis to strengthen the gateway.
- De Burgh's drawbridge consisted of an excavated pit spanned by a simple wooden platform that could be pulled inside the castle in an emergency. This unusual configuration was probably used because digging a moat across the solid rock peninsula would have been impractical. Most castle gatehouses used the more familiar pivoting drawbridge.

- Regardless of its configuration, a drawbridge was usually backed up by one or more portcullises. This heavy, iron-reinforced wooden grille could be lowered to block the gate—and if two were available, to trap attackers within the passageway. The portcullis was deployed by a windlass, which was often colocated with the drawbridge windlass above the gateway.

- De Burgh's 14th-century gatehouse upgrades included the addition of murder holes within the vaulted gateway and in the floor of a machicolation—a structure that spans between the two towers directly over the gateway.

- With the completion of the gatehouse, Carrickfergus Castle had transformed into a sophisticated technological system that exemplifies the military principle of defense in depth. To gain control of this castle, an enemy force attacking overland would need to fight through four distinct layers of defense from the gatehouse to the keep.

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10

Siegecraft Technologies

Siegecraft—the art and science of gaining entry into a fortified place—is a form of warfare that's nearly as old as warfare itself. In the Middle Ages, sieges were far more common than pitched battles. Medieval siege methods and technologies were, with few exceptions, inherited from the ancient Romans—mostly through the Byzantines, who continued to use and adapt the Roman systems for centuries after the Western empire fell. European military engineers also learned siegecraft through their contacts with more technologically advanced Muslim armies. This lecture looks at several systems used by medieval armies to fight their way into enemy-held castles.

Blockades

- The simplest and least risky form of siege was the blockade (also called investment), in which the attacking force surrounded a castle or fortified town, sealed it off from resupply, and then starved its population into submission. While this approach might seem like a sure bet that required only patience and a sufficient number of soldiers, in practice, it was fraught with major challenges that tended to increase over time.
- During the Siege of Antioch, conducted between October 1097 and June 1098, Crusaders suffered starvation and disease and were vulnerable to Turkish ambushes, and many knights simply gave up and went home—having fulfilled their feudal military service obligation to their lords.
- The rules of chivalry stipulated that, upon initiating a siege, the besieging commander would request the surrender of the defending garrison. If this offer was accepted, the defenders were allowed to depart unharmed; however, if it was refused, the besieging army was "entitled" to sack the castle or town—and kill all its inhabitants.
- Given these rules of engagement and the challenges of blockades, attackers often used intimidation, trickery, or treachery to provoke an early surrender and avoid prolonged sieges. But these tactics had many uncertainties associated with them.
- Besieging armies often had no alternative but to attempt a forced entry to a castle or fortified town. Logically, such entry could be achieved only by three possible routes—over the wall, under the wall, or through the wall—each of which required extensive technological assistance.

Scaling Ladders and Siege Towers (Belfries)

- The practice of attacking over a wall is called escalade. The simplest enabling technology for escalade is the scaling ladder—typically just a simple wooden ladder, sometimes augmented with iron hooks at the top to grip the enemy battlement. However, assault troops climbing the ladders were fully exposed to projectiles dropped or shot from the battlements, and ladders could easily be tipped away from the wall by defenders. Moreover, medieval sources often describe assaults that failed because the ladders turned out to be too short—or too weak to bear the weight of heavily armored men-at-arms.

A more robust alternative was the siege tower—also called a belfry—which functioned essentially as an armored mobile scaling ladder. Configurations varied widely, but the typical belfry was a multistory timber tower with an internal stairway enclosed by heavy wooden sheathing on the front and sides. The tower was usually at least 1 story taller than the wall it was designed to assault, so archers stationed on the top level could engage defenders on the wall walk in preparation for the deployment of a drawbridge on which assault troops could cross over to the enemy battlements.

The belfry's mobility was provided by either wheels or rollers, and propulsion was provided either by large numbers of men pushing or by teams of oxen pulling on ropes that were routed through pulleys to keep the animals outside of missile range.

Ancient Roman siege

Because it was so difficult to move, the belfry had to be assembled relatively near the enemy wall, and its planned route forward had to be meticulously prepared—a process that was impossible to conceal. Thus, the defenders would have had no doubt about the intended point of attack and could implement countermeasures accordingly.

Siege of Lisbon

Defenders often attempted to destroy belfries with incendiary weapons—flaming arrows or pots of flammable material launched by catapults. Another defensive strategy was to impede the machine's forward movement—for example, by tunneling beneath the expected route of advance, so the belfry would sink into the ground and be rendered useless.

Mining

A common alternative to escalade was mining—that is, tunneling beneath the enemy wall. This approach could be used to provide a route for assault troops to enter the castle; however, more often, miners dug only as far as the wall, then excavated a large chamber beneath its foundations. This chamber was then filled with combustible material and ignited. The wall collapsed into the void to create a breach, which could then be exploited by assault troops.

- The significant advantages of mining over escalade were that the tunnel could be constructed in secrecy and that the miners were protected from enemy projectiles as they worked. However, mining wasn't feasible if the castle was built directly on bedrock or if it had a water-filled moat. And mining could also be defeated.

During a siege, defenders often placed containers of water on the ground, just inside their curtain walls. When they saw ripples on the water's surface, they knew that mining was underway below, and they could initiate countermeasures to attack and drive off the enemy miners.

Battering Rams

- To go through a wall, a common approach was to hack through the stone masonry with picks and crowbars, usually at a vulnerable corner. But this was an extraordinarily dangerous job.

Battering ram

- A more impactful tool for breaching enemy walls was the battering ram—typically a massive tree trunk, tipped with an iron or bronze head and suspended from a mobile shed. The destructive power of a battering ram increased with the length of the ropes or chains from which the ram was suspended.

- The same countermeasures used against belfries—incendiary weapons and impediments to movement—were equally effective against rams. In addition, defenders often attempted to reduce a battering ram's effectiveness by lowering various devices intended to smash the ram, restrain its movement, or cushion its blows.

The Ballista and the Onager

- Medieval armies also attempted to attack stone walls from afar with artillery. The premier artillery weapon of the ancient world was the torsion catapult, called a palintone by the Greeks and a ballista by the Romans. The term *torsion* refers to twisting—and a torsion catapult is so named because its source of power is a pair of torsion springs, each composed of a bundle of twisted rope. In antiquity, the preferred material for these springs was animal sinew, which has an exceptionally high capacity to store elastic energy.

- To operate the ballista, a windlass was used to retract a slider—which held a trigger mechanism, a rope sling, and a projectile. As the slider was pulled rearward, the sling rotated the two throwing arms inward, and this rotation twisted the torsion springs. When the trigger was pulled, the springs drove the arms forward, and as the sling snapped tight, it launched the projectile.

- As the Roman Empire declined, the Roman army apparently couldn't maintain the high level of technical expertise required to continue operating the ballista, and by the 4th century, a simpler torsion catapult called the onager had taken its place. The onager had only one torsion spring driving a single throwing arm—a configuration that required the addition of a heavy padded frame to stop the forward motion of the arm.

Because of its simplicity, the onager was easier to build and operate than the ballista, but it was also much less mechanically efficient. Nonetheless, the onager remained the principal Byzantine artillery weapon for the first few centuries of the early Middle Ages.

- From an engineering perspective, both the ballista and the onager operated by storing elastic energy in their torsion springs, then transferring some of this energy to the projectile as kinetic energy. The percentage of the stored energy that's transferred to the projectile is the catapult's mechanical efficiency.
- The efficiency of the onager was quite low because much of the stored elastic energy was transferred to the heavy throwing arm and then wasted when the arm collided with the padded frame at the end of the fling. Relatively little of the stored energy was imparted to the projectile.
- Conversely, the mechanical efficiency of the ballista was very high because nearly all its stored elastic energy was transferred into the projectile. This occurred because the forward motion of the arms was stopped by the sling snapping tight—an action that imparted most of the arms' kinetic energy back into the projectile. Consequently, all other things being equal, the ballista would have had a substantially longer range than the onager.

The Traction Trebuchet (Mangonel)

- Before the onager could be widely adopted by Western armies, it was superseded by a fundamentally new technology—the traction trebuchet. Often called a mangonel in medieval sources, this machine was a human-powered catapult, consisting of a pivoting wooden throwing arm mounted on a pedestal. The short end of the arm was fitted with pulling ropes for the human operators, and the long end held a rope-and-leather sling that launched a stone projectile. One end of the sling was tied to the throwing arm, while the other incorporated an iron ring that slipped loosely over a finger extending from the end of the arm.

- As the operators pulled downward, the throwing arm rotated. This rotation caused the sling to whip around the arm's upper end until it reached the point where the ring slipped off the finger, thus unfolding the sling and releasing the projectile. The mangonel was typically operated by 20 to 100 people, depending on the size of the machine and the weight of the projectile; most stones weighed 10 to 15 pounds, though some might have been as heavy as 40 pounds.

- The mangonel was simpler than the onager. Because its unbalanced throwing arm naturally returned to the "ready" position after each fling, it didn't need a windlass or a trigger mechanism. This simplicity meant that mangonels could be built at the site of a siege using local materials.

During the Siege of Lisbon in 1147, two English mangonels operated by 100 men (working in shifts) launched 5000 projectiles in 10 hours. That's one shot every 7 seconds!

- Of course, no 40-pound projectile could breach a 10-foot-thick wall. Besieging armies used mangonels mostly as antipersonnel weapons—for example, to drive defenders from their wall walks as a belfry or battering ram was rolled forward. Mangonels were also mounted on castle towers and used to defend against sieges.

The Counterweight Trebuchet

- In the late 12th century, roughly 400 years after the traction trebuchet first appeared in Western Europe, engineers replaced the mangonel's human rope pullers with a heavy counterweight. The resulting machine—the counterweight trebuchet—quickly became the principal heavy artillery weapon of the era.

- A few medieval illustrations show the counterweight rigidly fixed to the short end of the throwing arm; however, most show the weight suspended from the arm like a pendulum, which was a more practical arrangement and was more mechanically efficient.

Trebuchet at Warwick Castle

- The source of the trebuchet's power was the gravitational potential energy of the raised counterweight. When the trigger was released, the counterweight fell, and its potential energy was converted into the kinetic energy of the counterweight, arm, and projectile in motion; because the counterweight and arm were so massive, they received most of this energy. But in a well-tuned pendulum counterweight trebuchet, most of the potential energy was transferred to the projectile as kinetic energy.

- The employment of these huge machines represented a major logistical challenge because they weren't mobile, couldn't be fabricated on site, and thus had to be transported in pieces. Perhaps for this reason, the mangonel remained in widespread use, even after the advent of the counterweight trebuchet.

- The story of the medieval catapult has a fascinating epilogue. In the 13th century, just as the gravity-driven trebuchet was becoming the era's dominant artillery weapon, a new arrow-shooting torsion catapult called the springald was introduced. With two torsion springs driving a pair of throwing arms and a sling, this machine was apparently an attempt to reconstruct the ancient Roman ballista—possibly based on surviving ancient treatises. And while the design of the springald is neither well documented nor fully understood, medieval sources suggest that it was used extensively in the defense of fortifications. And so, the story of medieval artillery—which began with the ballista—had come full circle.

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11

The Gunpowder Revolution

The gunpowder revolution refers to a series of events surrounding the development of gunpowder weapons in Europe from roughly 1300 to 1650. Gunpowder changed the world in profound ways, and in this sense, the term *revolution* is entirely appropriate. But what sort of revolution takes 350 years to play out? As this lecture shows, the answer is that there was a lot more to the gunpowder revolution than just the invention of gunpowder. For centuries after this discovery, artisans and engineers had to overcome a succession of daunting technological challenges that severely limited their ability to use this strange new substance as a weapon. Only when these challenges were overcome could the revolutionary impacts of gunpowder be fully realized. Thus, in the context of technological development, the gunpowder revolution was far more evolutionary than revolutionary. This evolutionary process is the subject of this lecture.

Combustion

- Gunpowder is a mixture of three materials:
  - sulfur—a naturally occurring mineral that burns at a relatively low temperature;
  - charcoal—a form of nearly pure carbon, created by burning hardwood with a restricted oxygen supply; and
  - saltpeter—a natural waste product of decomposing organic material whose key chemical component is potassium nitrate (KNO_3).
- These materials are mixed together in controlled proportions—ideally, 75% saltpeter, 10% sulfur, and 15% charcoal—then pulverized into a fine powder. This mixture produces what people perceive as an explosion, which is actually combustion occurring at a very rapid rate.
- Combustion is a chemical reaction in which a fuel combines with oxygen to produce combustion products and energy. If the oxygen supply is restricted, the combustion reaction slows and stops.
- In the chemical reaction associated with the combustion of gunpowder, sulfur combines with carbon (from the charcoal) and potassium nitrate (from the saltpeter) to create combustion products and a lot of energy. The sulfur and charcoal serve as fuel, and the potassium nitrate serves as an oxidant, providing all the oxygen needed to sustain combustion.
- When gunpowder is ignited, the sulfur burns first because of its low combustion temperature, and the resulting heat ignites the charcoal and shatters the potassium nitrate molecules, liberating oxygen. This internally supplied oxygen accelerates the reaction, which liberates more oxygen, further accelerating the reaction. The energy released by this chain reaction rapidly heats the combustion products to over 3000°C—and these superheated gases expand violently outward in all directions, creating a blast wave that produces the sound and shock that people experience as an explosion.

First Uses of Gunpowder

In the Middle Ages, the effects of gunpowder were so terrifying and inexplicable that it came to be called the devil's distillate.

- The recipe for gunpowder was probably discovered accidentally in the 9th century by Chinese alchemists who were attempting to formulate an elixir of immortality—a rather ironic origin for an invention that would shorten so many lives. Despite warnings about its dangers, artisans developed gunpowder's first practical application—pyrotechnics. Then, between the 10th and 13th centuries, firecrackers were transformed into weapons.

- Pyrotechnic makers discovered that they could leave one end of a firecracker open, so the burning combustion products would create a spectacular fountain of sparks and flame. Before long, some enterprising military engineer fastened one of these open-ended tubes onto the end of a spear to create the world's first hand-held gunpowder weapon—the fire lance—which could throw a shower of flame about 6 feet. Eventually, the open-ended tube was turned around to create a skyrocket or a rocket-powered projectile.

- The most consequential step in this process was the recognition that the fire lance could be made more deadly by packing shards of metal or broken pottery into the open end of the tube to create a primitive shotgun. This was a monumental conceptual leap, as all previous gunpowder weapons had used fire to produce a destructive effect. But this weapon used gunpowder only as fuel; the destructive effect was provided by the mechanical energy of projectiles blasted from the tube's open end.

- By the 13th century, this conceptual leap was fully realized in the first true gun. Properly called a hand cannon, this weapon replaced the tube with a heavy, cast-metal barrel. The projectile was a stone or metal ball or a large arrow called a garros, and the gunpowder was ignited by inserting a red-hot poker into the combustion chamber through a small touchhole.

- Over time, hand cannons were made progressively larger, so they could fire heavier projectiles. And when the weapon became too heavy to be operated by one man, it was strapped onto a wooden mount or wheeled carriage. Called an erupter, this was the first true gunpowder artillery weapon.

Early Gunpowder Weapons in Europe

- The earliest illustration of a European gunpowder weapon—from a manuscript of 1326—shows a vase-shaped gun shooting a garros. The oldest surviving physical example is the Loshult gun—a 12-inch-long cast-bronze hand cannon—similarly vase-shaped and dated to the first half of the 14th century.

Loshult cannon

- In 1326, the government of Florence issued a written order to procure cannons and ammunition for the town's defense. Scholars are not sure how this technology was transmitted to the West, but it was probably through Mongol attacks on the Arabs and subsequent clashes between Muslim and Christian armies on the Iberian Peninsula.

- Over the next 50 years, gunsmiths did a lot of experimentation. Most of these early guns were cast from bronze or copper, but some were forged from wrought iron. To forge an iron hand cannon, the smith hammered a red-hot bloom of iron into a flat sheet, then reheated it, wrapped it around a wooden mandrel, forge-welded the seam, closed off the rear end, and added a touchhole. This weapon—called a culverin—was necessarily quite small because the smelting technology of this era couldn't produce large blooms of iron.

- Progress in the design of gunpowder weapons continued to be constrained by the high cost of imported saltpeter until the late 1300s, when a process for producing saltpeter artificially was discovered. This development—one of the most important (yet underappreciated) enablers of the gunpowder revolution—prompted the establishment of saltpeter plantations all over Europe. And as the saltpeter supply increased, the falling price of gunpowder served as a powerful stimulus for innovation.

Wrought Iron Bombards

- Around 1370, smiths developed a new technique for forging larger wrought iron guns. These guns featured a cylindrical barrel made up of iron staves held in place by iron hoops. Stave-and-hoop guns used a removable wrought iron combustion chamber.

- These guns gave rise to the quintessential heavy artillery weapon of the late Middle Ages—the bombard. During that era, the term *bombard* was loosely applied to cannons of all sizes; but today, it's used specifically for the large-caliber siege guns of the late 14th and 15th centuries.

- The most famous medieval bombard is Mons Meg—a 15,000-pound monster, currently on display at Edinburgh Castle in Scotland. It was forged in Mons, Belgium, in 1449 for Philip the Good, duke of Burgundy, who then sent it as a gift to James II, king of Scots. With its 19-inch bore, Mons Meg could fire a 330-pound stone ball 2 miles—though when used in sieges, it would have been positioned closer to the enemy walls for greater destructive effect.

Like all wrought iron bombards, Mons Meg suffered from two major limitations. First, the logistical demands and cost associated with transporting and emplacing this massive weapon were staggering. Second, it was particularly vulnerable to catastrophic structural failures during firing. James II of Scotland, the proud owner of Mons Meg, was killed when another of his bombards exploded during a siege in 1460. And even though Mons Meg's combustion chamber and barrel were permanently connected, it also burst at this location during a ceremonial firing in 1680.

Mons Meg

Corned Powder

Prior to the 15th century, the greatest challenge in operating all gunpowder weapons was achieving consistency in the ignition of the powder charge. Misfires were common for three reasons. First, the potency of gunpowder could be drastically degraded by exposure to moisture. Second, gunpowder's constituent materials—sulfur, charcoal, and saltpeter—tended to segregate during transport. And third, the process of loading powder into a gun left very little margin for error. If gunpowder was packed either too tightly or too loosely into a combustion chamber, it wouldn't explode with full force.

- These problems were solved effectively (though quite accidentally) by another crucial technological advance—the invention of corned powder in the early 15th century. Corned powder was created by adding a small amount of liquid (usually distilled wine spirits or human urine) to the charcoal, sulfur, and saltpeter before they were mixed and pulverized. Then, this paste was dried to form hard pellets.

- The dried pellets proved to be highly moisture resistant and weren't susceptible to segregation. They also exploded with substantially more power than granular powder—an improvement that led to several dramatic changes in weapon design.

- Corned powder set the wrought iron bombard on a path to obsolescence because these guns simply weren't strong enough to withstand the increased internal pressure generated by corned powder. Cast bronze now became the metal of choice for guns of all sizes, and gun founders developed increasingly sophisticated casting techniques and design features to meet these new demands.

- Around the mid-15th century, a French artillerist named Samuel Besh invented the cast-iron cannonball—an important innovation that was enabled by three technological prerequisites—the strength of bronze guns, the explosive power of corned powder, and the increasing availability of cheap cast iron.

Iron cannonballs had three distinct advantages over stone projectiles:

- They were more destructive because iron is denser than stone.
- They were less expensive to produce because they were cast in a mold rather than carved by hand.
- Their sizes could be more easily standardized.

Trace Italienne

- In 1494, King Charles VIII of France invaded Italy with a 25,000-man army that included a corps of professional artillerists and 36 state-of-the-art cannons. During the campaign, these guns breached the previously impregnable castle of Monte San Giovanni in just 8 hours. It became evident that the castle's most important assets—the hardness and height of its stone walls—had become liabilities.

- The challenge posed by gunpowder artillery could be met only by a fundamentally new approach to fortification design. This approach—called the *trace italienne* system—was developed by some of the most brilliant minds of the Italian Renaissance, in direct response to the French invasion of 1494.

- In the *trace italienne* system, tall stone walls were replaced by low earthen ramparts and heart-shaped bastions, reinforced with low masonry revetments, and integrated with broad ditches and sloped embankments. These earthen structures could absorb cannonball impacts with minimal damage, and defensive cannons firing through well-protected embrasures could cover every inch of ground outside the defensive perimeter with interlocking fires. By the mid-16th century, cities all over Europe had built *trace italienne* fortifications.

The Matchlock

- As gunpowder artillery was rendering the castle obsolete, handguns were definitively ending the dominant role of the mounted man-at-arms on the battlefield—though, once again, the pace of change was more evolutionary than revolutionary. For more than a century after hand cannons were first used in Europe, their battlefield effectiveness was fundamentally limited by a basic user interface problem—the awkward process of igniting the powder charge with one hand while attempting to aim the weapon with the other.

- This problem wasn't solved adequately until around 1475, with the invention of the matchlock—a mechanism that allowed the gunner to fire his weapon by pulling a trigger. The matchlock trigger was a spring-loaded lever, linked to a pivoting arm—called the serpentine—which held a slow-burning match. When the gunner pulled the trigger, it lowered the match into a small pan filled with gunpowder, and the resulting flame propagated through the touchhole and into the chamber to fire the gun.

- The matchlock prompted major advances in handgun design, and by the late 1500s, a matchlock-equipped long gun—called the arquebus—had been widely adopted by European and Ottoman armies. The obsolescence of the castle, the knight's loss of military dominance, the declining autonomy of local lords, and the rise of professional armies signaled the demise of the quintessential medieval institution—feudalism. Thus, the gunpowder revolution played a key role in the transition from the Middle Ages to the early modern era.

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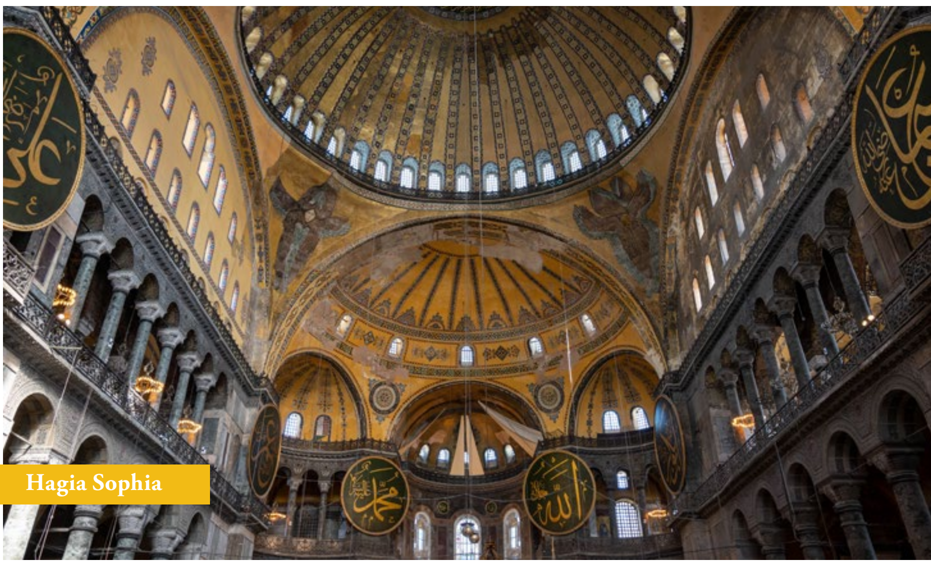
12

Hagia Sophia: Byzantine Architectural Marvel

This lecture is the first in a series of seven that address the great structures of the medieval world. Hagia Sophia is a worthy place to start, not only because it's the first truly great structure of the Middle Ages but also because it serves as an effective vehicle for exploring the basic structural engineering concepts that will be applied throughout the remainder of the course. Unlike many modern structures, the stylistic and functional configuration of Hagia Sophia—that is, its architecture—and the underlying structural engineering are inseparable. So, by understanding Hagia Sophia as a technological system, one can also understand it as an architectural wonder.

A Cathedral Worthy of a Great Empire

- On December 27, 537, in the presence of Byzantine Emperor Justinian I, the newly completed Church of the Holy Wisdom—Hagia Sophia—was consecrated in the heart of the imperial capital, Constantinople (modern Istanbul). It hardly seemed possible that such a grand building could have been erected in only 6 years.
- Justinian made the unconventional decision to have his church designed not by a master builder but by two gifted Greek mathematicians—Isidore of Miletus and Anthemius of Tralles. Neither was trained in architecture, but both had the conceptual skills to envision a structure that was as much a work of geometry as a work of engineering. They were given virtually unlimited resources and a workforce of 10,000 men. To decorate the interior, Justinian imported exquisite marbles and hired sculptors and mosaic artists from all over the Mediterranean world.
- The cathedral would blend old and new—evoking the monumental ancient structures of imperial Rome while also meeting the liturgical demands of the Christian church in a compelling new way. The



Hagia Sophia

centerpiece of Hagia Sophia is a great dome that measures 107 feet in diameter, rises 180 feet above the floor, and features 40 windows that fill the nave with ethereal light.

Hagia Sophia became the greatest church in Christendom—a building so unique in conception that it would define the architectural style now called Byzantine, so monumental that it would remain the world's largest church for more than 1000 years, and so awe-inspiring that, even today, it's often described as one of the world's most beautiful enclosed spaces.

Structural Materials in the Middle Ages

- Recall from the discussion of longbows (lecture 8) that whenever a structural element is subjected to a load, it experiences either tension or compression. Many structural materials behave quite differently in tension and compression.

- During the medieval era, only four structural materials were readily available to builders—stone, brick, wood, and wrought iron—all of which have significant limitations. Stone is very strong in compression but weak in tension, and it's expensive. Brick is also weak in tension and nearly as strong as stone in compression, but brick is less expensive because it can be mass-produced, while stone must be carved by hand.

- In medieval masonry construction, the tensile weakness of both stone and brick was exacerbated by the soft, lime-based mortar that was used to join bricks and stone blocks together. Such a masonry wall works fine in compression, but when subjected to tension, it simply pulls apart at the joints.

- Wood and wrought iron are reasonably strong in both tension and compression; however, wood is vulnerable to fire and rot. And during the Middle Ages, there simply wasn't enough iron available for use in large structural applications.

Structural Elements of Hagia Sophia

- The structural system of Hagia Sophia was built entirely of brick, except for its main load-bearing columns, which are stone, and a few wrought iron reinforcing bars and clamps. Because brick and stone are weak in tension, the structure had to be designed in such a way that all of its brick and stone elements carry load only in compression. To meet this challenge, Isidore and Anthemius used four types of structural elements—the column, arch, vault, and dome—in their design.

- A column is a vertically oriented structural element that's used to support a load above ground level and carries this load in compression. An arch is normally used to span across a horizontal distance. It carries load entirely in compression, and when an arch is loaded, it tends to flatten, and its ends slide outward. This tendency—called thrust—must be restrained, or the arch will be incapable of carrying load.

- In medieval structures, such as Hagia Sophia, arches are often positioned on top of columns, and the thrust is restrained with wide, heavy elements—called buttresses—which stabilize the columns by adding both width and weight. When multiple columns and arches are placed side by side, the resulting structure is called an arcade. Within an arcade, the thrust of each interior arch is counterbalanced by the thrust of the adjacent arches. The outermost arches require additional lateral support—typically in the form of buttresses or heavy columns.

- Arches can also be used to enclose a space—simply by extruding the two-dimensional form into the third dimension to create a cylindrical roof, called a barrel vault. As an architectural entity, the barrel vault has two major limitations: Its outer ends must be continuously supported from below, typically by heavy walls, and natural light can enter the enclosed space only through the open ends of the vault.

- These limitations can be addressed by intersecting two barrel vaults at a right angle and then removing the unwanted material to create a groin vault—a significantly more versatile architectural form that can be supported on four columns and can admit light from any direction.

The column, arch, and vault are the basic building blocks of most medieval structures. Four columns, four arches, and a groin vault can be combined to form a square bay, which can be replicated to create an enclosed space of virtually any size.

- A dome carries load quite differently in the meridional (vertical) and circumferential (horizontal) directions. Like an arch, the loaded dome tends to squash downward and spread outward, thus causing compression along the meridians. But as the dome flattens, the circumferential lines tend to stretch outward—a phenomenon called circumferential tension—and cracks can form along the meridians.

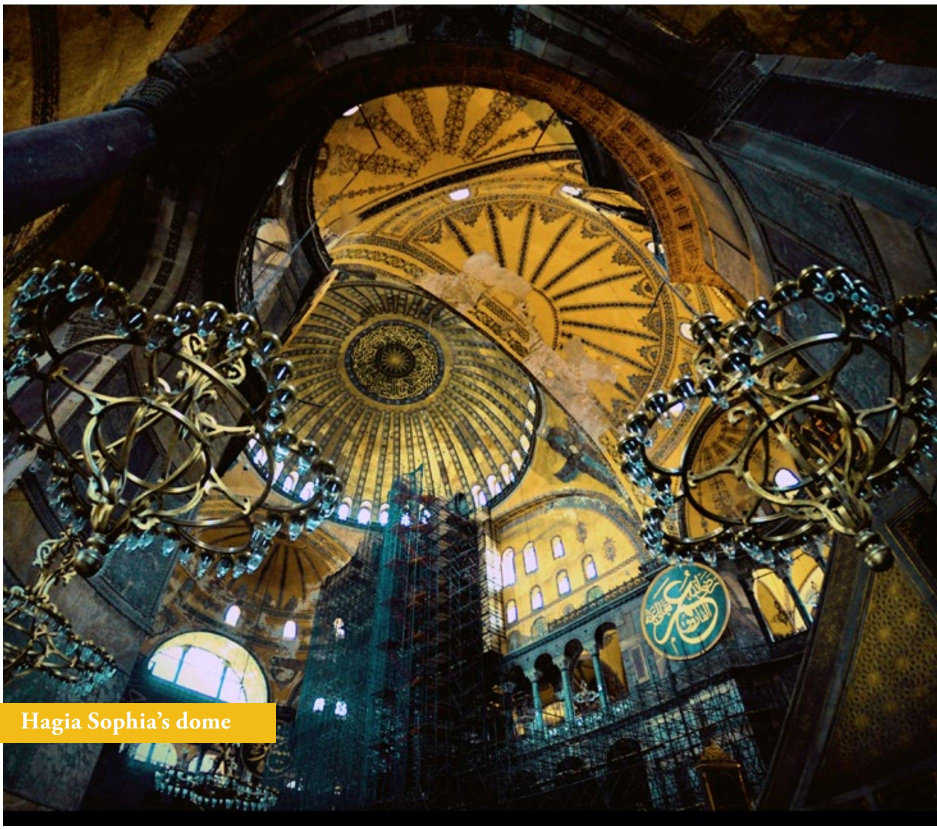
- If a dome is made of brick—as is the dome of Hagia Sophia—cracks will form in just this way because the material has essentially zero strength in tension. Once this cracking has occurred, the dome is effectively transformed into a series of discrete arches, arranged radially around a vertical axis. And like all arches, they experience outward thrust—which must be restrained, or the dome will collapse. One approach to restraining outward thrust is to place four heavy buttresses perpendicular to each other, so the dome is prevented from spreading outward in all four cardinal directions.

Hagia Sophia's Original Dome

- Hagia Sophia's main building has a rectangular floorplan measuring 250 by 220 feet. A large narthex (entry hall) extends from the west end of this rectangle, and a semicircular apse—which originally housed the high altar—extends from the east end. At the core of the church is the nave—a vast, open space, 250 feet long and over 100 feet wide. On either side of the nave are aisles at ground level and galleries on the level above. The great dome is centered on the nave, with its base perched 130 feet above the floor.

- Because the nave was, by design, an uninterrupted open space, no structural supports could be placed directly below the dome. Thus, the dome's entire support system had to be configured in a way that didn't intrude upon the nave at all. The principal supporting elements are four massive stone columns—called piers—positioned just outside the nave. These piers support four great arches, which delineate a square bay, and the dome is directly supported on these arches.

The original dome of Hagia Sophia sustained severe damage during an earthquake in 557, suffered a partial collapse the following year, and was replaced by a new dome designed with a fundamentally different configuration. The 6th-century sources suggest that the original dome had a rise of only 28 feet—and thus was much shallower than the current 48-foot-tall dome. The original probably also had 40 windows around its base, just as the current dome does.



Hagia Sophia's dome

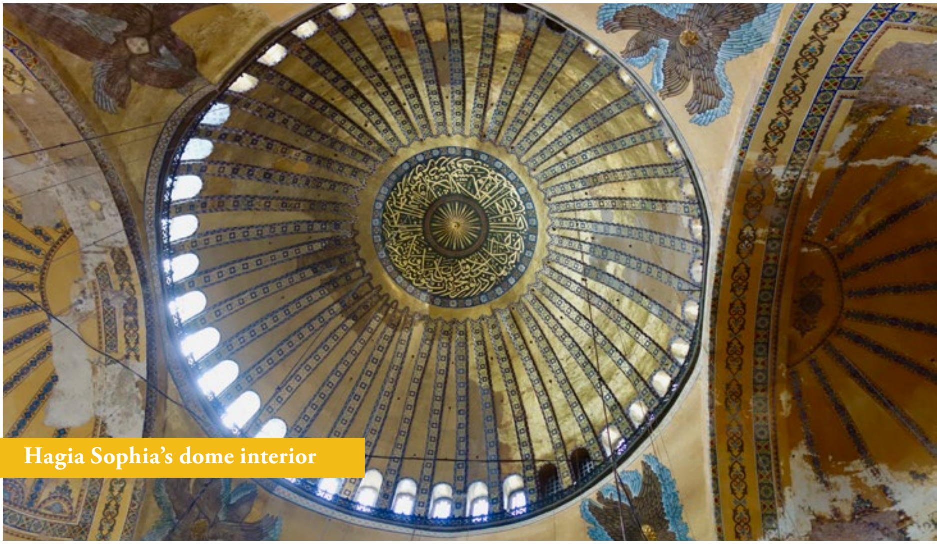
- Architectural historians Kenneth Conant and Rabun Taylor proposed two very different alternative configurations. Although Taylor provided a strong justification for his proposal, Conant's proposed configuration is more stylistically consistent with other original portions of the structure, and it's also more geometrically elegant than Taylor's proposal.

- It's useful to conceptualize the hemispherical surface as two distinct entities—a shallow dome, which sits on top of the great arches, and four spherically curved triangles, called pendentives, which fill the spaces between the dome and the arches.

- The shallowness of the original dome posed a major structural engineering challenge such that the design of Hagia Sophia had to incorporate a very robust structural system for restraining the extremely high outward thrust of the dome. Isidore and Anthemius designed two independent structural systems. In the system oriented in the north–south direction, the main piers are prevented from tipping outward by massive buttresses, each of which is connected to its associated pier with two pairs of heavy arches. The great arch is laterally stabilized by a massive buttress vault, by additional brick fill over the vault, and by upward extensions of the buttresses.

- In the system oriented in the east–west direction, two large buttresses were placed at each end of the nave with a buttress vault spanning between them. These buttresses are connected to the piers by curved two-level arcades—called exedrae—and each buttress vault is connected to its associated great arch with a huge semidome (or half dome and two smaller semidomes over the exedrae). Additional lateral support is provided to the western buttresses by the columns, arches, and vaults of the two-level narthex and to the eastern buttresses by the apse.

- Subtle design and construction issues contributed to the collapse of the original dome in 558—only 20 years after its construction. The most important of these issues resulted from the incredible speed at which Hagia Sophia was built. Lime-based mortar hardens through a chemical reaction with carbon dioxide in the surrounding air. Because the mortar joints deep within the massive piers and buttresses had little exposure to air, they would have taken many years to cure fully. Thus, during construction, as soon as the dome started supporting its own weight, those soft mortar joints slowly deformed in response to the dome's immense outward thrust. Consequently, the piers and great arches tipped slowly outward by as much as 2 feet—displacements that are still present in the structure today.



Hagia Sophia's dome interior

This issue was exacerbated by a significant design flaw. Each pier was pierced by a gallery-level passageway, which weakened the piers and contributed to their outward lean, which in turn compromised the structural stability of the dome. This failure mode is called snap-through instability, and it was probably a significant contributor to the Hagia Sophia collapse.

Rebuilding the Dome

After the collapse, Emperor Justinian ordered the dome rebuilt. To supervise the work, he hired Isidore the Younger—a nephew of the original designer. Three aspects of the new design suggest that young Isidore correctly identified the causes of the original dome's failure and addressed these issues in its replacement:

- The new dome is 20 feet taller than the original and thus has substantially reduced outward thrust.
- The inside of the dome is ribbed; the thicker ribs provide enhanced stiffness, and thinner segments reduce the dome's weight—thus further reducing its outward thrust.
- The raised ribs pass between the windows, thus channeling the dome's weight and thrust around these points of weakness to 40 robust external buttresses, which provide effective lateral support without detracting from the internal appearance of the dome.

The rebuilt dome survived intact for more than 4 centuries, until a major earthquake collapsed its western half in 989. Another quake in 1346 collapsed a portion of the eastern half; in both instances, the dome was restored to the configuration devised by Isidore the Younger. And despite numerous earthquakes since then, this great structure has survived to the present day—albeit with many scars and with a shape that has wandered noticeably from its original circular plan.

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13

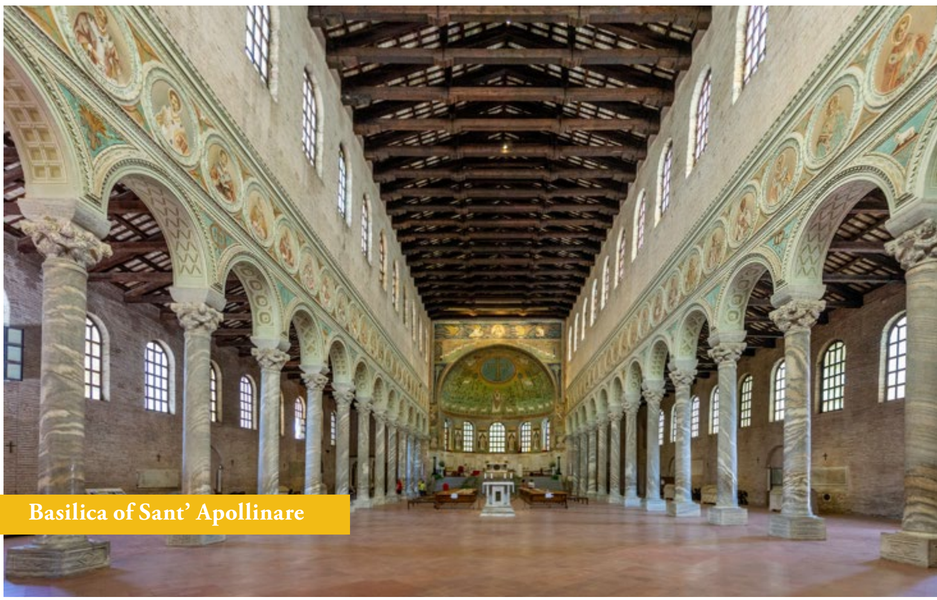
From Romanesque to Gothic

In Western Europe, the fall of Rome left builders with neither the technical expertise nor the resources to attempt structures of such grand scale and sophistication as the great 6th-century church of Hagia Sophia. Rather, they generally adopted a modest Roman civic building—the basilica—as the basis for their churches. It wasn't until the 11th century that a distinct new architectural style emerged in Western Europe. Today, this style is called Romanesque because it borrowed some ancient Roman elements, but it also has its own unique character. This lecture examines the historical and technological developments that set the stage for the birth of medieval architecture.

The Roman-Style Basilica

- The simple Roman-style basilica remained the structural state of the art throughout the early Middle Ages. A fine example of this style is the Basilica of Sant' Apollinare in Classe in Ravenna, Italy. Although it was consecrated in 549—and thus is contemporary with Hagia Sophia—it reflects the more modest aspirations of Christian communities in the early medieval West. The plan of Sant' Apollinare includes a central nave with aisles on both sides, a narthex at the west end, and a semicircular apse—which faces eastward, toward Jerusalem.

- The basilica's structural system is also quite simple. The aisles are enclosed by solid, load-bearing walls. The nave is separated from the aisles by two arcades, each consisting of classical columns surmounted by semicircular arches. The triangular spaces above the arches are filled by masonry elements called spandrels, which are integrated with the upper walls of the nave. The roof structure consists of heavy wooden trusses supporting a clay-tile roof. Similar truss structures are used to cover the aisles.



Basilica of Sant' Apollinare

- A truss is an assemblage of structural members arranged in interconnected triangles to form a rigid framework. The diagonal members of a truss carry load entirely in compression, and they generate outward thrust, which must be resisted by supports to prevent collapse.

- The key difference between a truss and an arch is that the truss doesn't need external lateral restraint to resist the outward thrust of the diagonals because that resistance is accomplished internally by the horizontal member—called a tie beam—which ties the ends of the diagonals together and prevents them from spreading outward. In performing this function, the tie beam stretches and thus is in tension, as is the vertical member—called the king post.

- Another key difference between the truss and the arch is that the members of a truss experience both compression and tension—so the structure must be built of a material that's capable of carrying load in both modes. In the medieval world, the only readily available material that satisfied this criterion was wood.

Medieval builders did not invent the truss, but they took this technology to an entirely new level of structural sophistication and craftsmanship.

Romanesque Style

- The unique character of the Romanesque style is beautifully illustrated by the Cathedral of Santiago de Compostela, designed by a master builder named Bernard the Elder and constructed between 1075 and 1211 in northwestern Spain. Like most Romanesque churches, Santiago de Compostela has retained the nave, aisles, and apse of the Roman-style basilica; however, with the addition of perpendicular extensions—called transepts—the floorplan now takes the form of a Latin cross.

- A tower is positioned directly over the intersection of the nave and transepts, and two additional towers flank the narthex at the western end of the nave. The apse has been expanded to include a semicircular aisle—called the ambulatory—and a series of chapels radiate outward from the ambulatory. The apse, ambulatory, and chapels are collectively called the chancel.

- Santiago de Compostela illustrates five characteristic features of Romanesque architecture:
  - subdivision of the interior space into square or rectangular modules, called bays;
  - semicircular arches;
  - massive walls and piers;
  - small windows; and
  - elegant stone vaulting that replaced the wooden trusses of the Roman-style basilica.

Although Santiago de Compostela is the largest Romanesque church in Spain, its fame derives not from its style or its size but from its site as the reputed burial place of Saint James and as a revered pilgrimage destination from the 9th century to the present day.

The Structural System of Santiago de Compostela

- Compound piers separate the nave from the aisles. A compound pier is a column that's composed of multiple parallel elements—in this case, a large central square shaft and four smaller cylindrical elements called colonnettes.
- Each outer wall incorporates an engaged column—which, together with the piers, defines the corners of the aisle bays. The walls and piers are composed of multiple layers of stone, called courses. Within each course, the outer faces are solid stone blocks, cut and finished with great precision and joined together with mortar—a mixture of lime, sand, and water. The void between the outer faces is filled with a mixture of mortar and rubble.

Santiago de Compostela

- In Romanesque architecture, each pier and column is topped with an intricately decorated capital, which also serves as the impost—or base—for the heavy semicircular stone arches (and spandrels) of the arcade. These arches span from pier to pier in the east–west direction, and additional arches span across the aisles in the north–south direction.

- Groin vaulting serves as both the ceiling of each aisle bay and the floor of the upper-level galleries. The principal architectural advantage of groin vaulting is that it's open on all four sides—and thus allows for better interior illumination. However, the groin-vaulted bays also demonstrate an inherent limitation in Romanesque architecture. The semicircular groin-vaulting configuration is only possible if the bay it covers is square.

- Another major element of the structural system is the triforium—a pair of open arcades that serve as the inner walls of the upper-level galleries. Bernard's design included upper-level transverse arches to provide lateral support for the triforium walls. These arches resisted the outward thrust of the nave arches and barrel vaults, which could cause the triforium to topple outward if left unsupported. With those elements in place, the nave arches, barrel vaults, and additional half vaults could be installed.

Not all Romanesque churches have a triforium or compound piers, but these features would eventually be used in nearly all Gothic cathedrals.

- Bernard reinforced the exterior walls with heavy buttresses and buttress vaults, which effectively stabilize the entire structural system through their width and mass. And because the strength of these walls was so essential, he kept the windows relatively small. Consequently, the interior is very dark.

- Bernard could have included clerestory windows in his design by using groin vaulting rather than barrel vaulting over the nave. There are several possible reasons why he didn't, but one is almost certainly related to the fundamental limitation that symmetrical semicircular groin vaulting can only be used over a square bay. The nave is twice as wide as the aisles, and because the pier spacing is controlled by the square bays of the aisles, the nave bays can't be square. Each is a rectangle, two times wider than it is deep.

Many characteristically Romanesque architectural features were strongly influenced by the demands of structural load-carrying—especially by the need to restrain the outward thrust generated by the heavy stone vaults.

Solutions to the Romanesque Vaulting Problems

- The limitation of symmetrical semicircular groin vaulting was a major architectural problem that confronted all Romanesque church builders, and they responded with at least six distinctly different solutions. The simplest solution was to forego vaulting entirely, in favor of the wooden trusses of the older Roman-style basilica.

- Another solution was to use barrel vaulting, which can be installed over rectangular bays with no special accommodation—as at Santiago de Compostela. However, this approach precludes the use of clerestory windows and thus results in a poorly illuminated nave.

- A clever alternative that does allow for clerestory windows is exemplified by Speyer Cathedral in Germany, where adjacent pairs of rectangular nave bays were combined to create square bays. Only every other pier supports a transverse arch, while the intermediate piers support only the small arches framing the clerestory windows. Variations on this four-part (quadripartite) theme and other approaches contributed to the rich diversity seen in surviving Romanesque churches today.

- The final solution to the Romanesque vaulting problem was the pointed arch—an invention that would eventually become intimately associated with Gothic architecture. One of northern Europe's earliest uses of pointed arches can be seen at Durham Cathedral, constructed between 1093 and 1133 and often regarded as the finest Romanesque building in England.

Durham Cathedral

Durham Cathedral's arches and vaults predate the creation of the first true Gothic church in 1144, but they were critically important steps toward the forthcoming architectural revolution.

- The key geometric characteristic of a pointed arch is that its height is not constrained to half its span—as is the semicircular arch. Because of this characteristic, the nave arches and clerestory arches could now be made equal in height, even though their spans differed substantially. Thus, quadripartite vaulting could be used with rectangular nave bays, without special accommodations.

- The pointed arch also offers a significant structural engineering advantage in that it generates less outward thrust than a semicircular arch of the same span. For a given span, outward thrust decreases in direct proportion to increasing height.

- Credit for the invention of the pointed arch probably belongs to Muslim builders, who were using them for over a century before they first appeared in Europe. A stunning example is the 10th-century dome over the mihrab at the Great Mosque of Córdoba in Al-Andalus. Its octagonal dome is formed from eight semicircular arches; but because each arch spans across two sides of the octagon, the intersecting semicircles create pointed arches—which also serve as ribs that reinforce the dome.

- Based on this and other examples, Muslim builders are also credited with the invention of the ribbed vault—another feature that later would contribute immeasurably to Gothic architecture. Ribbed vaulting offered important architectural and engineering advantages over groin vaulting without ribs. From an aesthetic perspective, the ribs add visual interest by accentuating the intersections between the vault compartments; from a structural perspective, they significantly increase the vault's strength and stiffness.

- By the early 12th century, most of the individual features associated with Gothic architecture had been developed and were being used in various forms all over Europe. The next lecture explores how all the pieces were put together in a way that created both a fundamentally new architectural paradigm and a revolutionary new approach to structural load-carrying.

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14

The Gothic Stone Skeleton

If medieval master masons had none of the science that modern engineers use to guide their designs, how did they build the magnificent cathedrals? Medieval sources provide very little definitive information to answer this question. Fortunately, two highly reliable sources of information exist. First, more than 100 cathedrals have survived to the present day, and—like medieval castles—these great structures reveal much about how they came into being. Second, in general, the construction process is guided by a certain logic that, in many instances, simply couldn't be violated without provoking a disaster. Using a model, this lecture explores the most likely construction sequence that would have been used to build the nave of Amiens Cathedral. Located in France, the cathedral is the epitome of High Gothic architecture and a 13th-century engineering marvel. The model will reveal some of the unique challenges that confronted the medieval master mason.

A Vision of Light and Height

- Throughout the Middle Ages, the abbey church of Saint-Denis was a very important place. Located in a northern suburb of Paris, the church and its associated shrine mark the burial place of the city's first bishop, Saint Denis, who was martyred by the Romans in the 3rd century. In 632, the Frankish king established a Benedictine monastery on the site, and in the 8th century, the church was rebuilt by the first Carolingian king, Pepin the Short. After his death, Pepin was buried in the church—as were most of the French kings from the 10th century onward.

- In the 12th century, the abbey of Saint-Denis was led by a man of extraordinary vision—Abbot Suger—who initiated a major reconstruction of the church around 1135.

- To achieve his vision of using architecture to draw worshippers closer to God, he and his master builder employed all the features now associated with Gothic architecture:

    - tall interior spaces accentuated by slender piers,
    - pointed arches,
    - ribbed vaulting, and
    - large stained-glass windows.

None of the features of Gothic-style architecture were new inventions; all had been used individually in Romanesque and earlier Islamic buildings. But Abbot Suger combined them in an unprecedented way—using verticality to draw worshippers' eyes and minds upward and ethereal light to evoke the glory of God.

- On June 11, 1144, the rebuilt chancel of the abbey church of Saint-Denis was consecrated. On that day, the Gothic architectural style was born. The power of Suger's vision is evident in the rapid spread of the Gothic style after 1144. And as the style spread, it continued to evolve toward ever-greater height, larger windows, and more refined proportions. The epitome of High Gothic architecture—Amiens Cathedral—was built about a century later.

Construction of Amiens Cathedral's Nave

Every cathedral was commissioned by a patron, who then hired a single individual—called a master builder or master mason—who was responsible for everything from designing the structure and all its embellishments to supervising a workforce that included local laborers as well as itinerant specialists who worked on projects all over Europe.

Amiens Cathedral

Foundation and Arcade

The first phase of construction at Amiens was to excavate for, and then build, the foundation—a series of massive stone walls, oriented in both the longitudinal (east–west) direction and the transverse (north–south) direction. These walls intersect beneath the planned locations of the main piers and buttresses. They are 28 feet deep, and they taper outward from top to bottom to distribute the cathedral's immense weight over a broad area of soil beneath the foundation.

- The next phase was to build the arcade. The principal elements of this structural system are two rows of compound piers, which support the arches of the arcade and, thus, define the sides of the nave. Two additional rows of piers support the arches that frame the aisle windows and are integrated with heavy buttresses that extend outward from these walls.

- Next, transverse arches were built across the aisles, thus subdividing the aisles into square bays. Each bay was then covered with a ribbed quadripartite groin vault, consisting of four diagonal ribs joined to a cylindrical keystone and four thin stone shells—called webs—each of which fills the triangular space between two adjacent ribs. To complete the arcade level, the piers and buttresses were extended upward, and spandrels were added above the arches.

Triforium, Clerestory, and Buttresses

- The triforium, built immediately above the main arcade, is crowned by a magnificent clerestory—consisting of slender piers, interconnected by acutely pointed arches, spandrels, and a parapet walkway.

- As the triforium and clerestory were being erected, buttresses would have been extended upward at more or less the same pace. These massive elements would eventually become flying buttresses—another defining feature of Gothic architecture. Their main purpose is to resist the outward thrust of the nave arches and vaults.

- The buttresses are physically separated from the nave, so they won't intrude upon the interior space and won't block the passage of light through the clerestory windows. However, they can't perform their structural function without a physical connection to the clerestory piers. This connection was eventually made by half arches—called flyers—two of which span across the aisle between each buttress and its associated pier.

Enclosing the nave with a permanent roof involved building an elaborate attic structure, which consists of large, steeply pitched timber trusses supporting a wooden roof deck and an outer waterproofing layer of lead sheeting. Similar roof structures were erected over the aisle vaulting.

One of the most underappreciated technological features of the Gothic cathedral is the roof drainage system. Rain runoff is captured in a stone gutter in the top of the nave wall. The gutter empties through a conduit into a trough on top of the upper flyer, then down to the buttress, where it's expelled through the mouths of two gargoyles.

Flying buttresses of the Notre-Dame

Arches and Vaulting Ribs

The next step in construction would have been to erect the great arches and the vaulting ribs that span across the nave—a distance of over 40 feet. These arches spring from the capital atop the innermost colonnette on each pier and become independent structural entities only when they reach a significant distance above the impost. This is a fascinating feature of Gothic masonry construction, called the tas-de-charge.

- The tas-de-charge is a testament to the beauty, precision, and ingenuity of Gothic stonemasonry. This feature contributes to the Gothic aesthetic by making the arches and ribs seem to sprout organically from their supporting pier; it also significantly enhances the structural integrity of this critical node and facilitated construction by ensuring that the temporary centering units used to assemble the arches and ribs didn’t interfere with each other at the pier.

- As these arches and ribs were being assembled, construction would also have begun on the flyers of the flying buttresses. The flyers push inward as the arches are pushing outward; thus, to prevent an imbalance of forces in either the inward or outward direction, the centering units supporting the arches, ribs, vaults, and flyers of a given bay had to be lowered simultaneously.

Great windows and vaults of the Amiens Cathedral

- Quadripartite vaulting webs form the ceiling of the nave. Medieval masons performed this task by positioning thousands of precisely shaped stone blocks in carefully planned courses while perched on crude scaffolding suspended more than 100 feet above the floor. This achievement is among the greatest marvels of medieval construction.

- Two aspects of the vaulting's configuration are quite unexpected. First, the use of pointed arches should make stilting unnecessary. Recall that stilting is the practice of elevating the short-spanning arches of a rectangular vault so that the tops of their associated vault compartments will be at the same elevation as those of the long-spanning arches. Yet, the clerestory arches are indeed stilted. The reason for this is light—a stilted arch provides a significantly larger window opening.

- Second, the use of pointed arches should also make the use of cambered vaults unnecessary, but the vaults are indeed cambered; that is, the ridge of the vault is curved, thus creating a slightly dome-shaped surface. The reason is that camber strengthens and stiffens the vault. Gothic builders applied this principle to build vaults with incredibly thin webs, which not only economized on materials but also reduced the vaults' weight—reducing their outward thrust and thereby allowing for taller naves, lighter supporting structures, and larger windows.

An Engineering Marvel

- Amiens Cathedral represents a revolutionary development in structural engineering. This system fundamentally changed the structural load-carrying paradigm that had been used for millennia in monumental masonry construction. In the traditional load-carrying paradigm—which is best illustrated by Hagia Sophia—the internal forces are dispersed, and their intensity decreases as they propagate outward.

- For the sole purpose of creating huge window openings, the Gothic structural system focuses internal forces, rather than dispersing them. The outward thrust of the vaulting is carried by the arches and ribs to the corner of each vault, where it's concentrated and then channeled along a clearly delineated load path—from the pier through the lower flyer into the buttress and then down to the foundation—with little or no dispersion.

Pinnacles—the characteristically Gothic stone appendages—perform an important structural function. As internal force is transmitted through the flyers, the weight of the pinnacle helps deflect the load path downward into the buttress. Without this beneficial effect, the upper portion of the buttress would shear off in a high wind.

- The Gothic engineering system represents a distinctly modern paradigm for structural load-carrying. For example, in modern skyscrapers, wind loads are applied across the broad surfaces of walls, but the resulting internal forces are then concentrated into a skeleton of discrete beams and columns, then transmitted down to the building foundation along well-defined load paths.

- Modern engineers have two huge advantages over their medieval ancestors: powerful science-based analysis tools that can accurately predict the flow of internal forces through structures and versatile materials—like structural steel—that are ductile and equally strong in tension and compression.

- The Gothic stone skeleton had to be masterfully configured so that the load path would carry load entirely in compression. The slightest occurrence of tension anywhere along this path, under any loading condition, could cause a collapse.

The only known major failure of a Gothic cathedral—the collapse of Beauvais Cathedral in 1284—was probably caused by a minor occurrence of wind-induced tension in one of the buttresses.

- Based on a thorough analysis of the cathedrals built during the 12th and 13th centuries, a Princeton University scholar named Robert Mark concluded that, to achieve such incredible outcomes, master masons used an empirical design approach that was both systematic and collaborative. As they pursued the overarching goals of height and light, they carefully observed the performance of existing structures and made adjustments in response to problems. The evident, systematic progression in the design of cathedrals demonstrates that the master masons of this era formed a community of practice and learned from each other.

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15

Structural Marvels in Wood

Much of the medieval world was built of wood. It was inexpensive and readily available; it could be cut, shaped, and fastened with simple hand tools; and it provided several advantageous mechanical properties—most notably, its ample strength in both tension and compression. This lecture looks at three important wooden structures—each of which represents a significant engineering advance. These examples represent different building types, locations, and cultural influences—and thus demonstrate the versatility of wood and the broad scope of its architectural applications.

The Attic of Notre-Dame Cathedral

- On April 15, 2019, a fire broke out within the timber-framed attic of the most beloved of all Gothic cathedrals—Notre-Dame in Paris. When the cathedral's iconic spire collapsed, its massive timbers smashed through the stone vaults below. The resulting draft fed the flames, which quickly spread to the entire attic. By the time the blaze was finally brought under control, most of the 800-year-old oak roof structure had been incinerated.
- Donors pledged more than €1 billion to fund the reconstruction, and the French government decided that the rebuilt structure would adhere as closely as possible to the original medieval design. The cathedral reopened its doors at the end of 2024.

Notre-Dame in Paris

- Notre-Dame's original roof system was brilliant in conception, thoughtfully engineered in every detail, and adapted to the resource constraints of the era. To appreciate the structure as a technological innovation, one must first understand the traditional type of roof system it replaced.

Traditional Basilica Roof System

- Consistent with ancient Roman practice, timber-roofed Romanesque basilicas generally used a system of heavy trusses, which spanned across the nave walls and were directly supported on longitudinal timbers called wall plates. Seated on top of the trusses were a ridge beam; additional longitudinal timbers, called purlins; and closely spaced rafters. Smaller longitudinal boards—called battens—directly supported the terra-cotta roof tiles.

- The weight of the tiles was transmitted from the battens to the rafters, then to the purlins and the ridge beam, then to the trusses, then to the wall plates, and then down into the walls. Despite being effective and efficient, the basilica roof system had three major limitations:

  - The pitch of the roof (its slope) had to be quite shallow because the roof tiles weren't mechanically connected to the battens and, thus, could be easily dislodged if the pitch was too steep.

  - To avoid large roof overhangs, the shallow pitch and substantial depth of this multilayered system required excessively thick walls to create a clean interface between the roof deck and the walls.

  - Because a shallow-pitched roof retains more snow in the wintertime, the trusses required heavy timbers to carry this load.

- For these reasons, the traditional basilica roof structure would have been unsuitable for Gothic cathedrals, so builders had to devise a fundamentally new approach. The first cathedral to use this approach was Notre-Dame.

Notre-Dame's Roof Structure

- The cathedral's chancel was built and placed into service before the remainder of the structure was begun. Thus, the chancel attic—completed around 1182—was the earliest implementation of the new system. By the time the nave attic was built in the early 13th century, any issues that had been encountered previously had been resolved. Like the basilica roof, the nave attic was supported on two pairs of longitudinal wall plates, positioned on top of the nave walls. However, the bearing surface was only about 2 feet wide and was perched 115 feet above the floor—a set of conditions that presented enormous engineering and construction challenges.

- The wall plates supported 11 wooden trusses, spaced at 10-foot intervals and spanning nearly 50 feet across the nave. They defined a very steep roof pitch, which addressed several shortcomings of the shallow-pitched basilica roof but resulted in very tall trusses that required several significant structural adaptations.

- The main load-carrying members of each truss were its two diagonals (called principal rafters), the horizontal tie beam, and the vertical king post. The principal rafters carried load primarily in compression, while the tie beam acted in tension to prevent the rafters from splaying outward. The king post functioned as a hanger—meaning that a load suspended from it was effectively hanging from the top of the truss.

Wooden frames of Notre-Dame Cathedral in Paris

- Because the rafters were long and relatively slender, they were highly vulnerable to failure through buckling and bending. To prevent these failures, the designer added another pair of diagonals—called passing braces—which stiffened the truss and shared the compressive force borne by the principal rafters. He also added three horizontal members—called collars—to brace the principal rafters against inward bending and buckling.

- Another challenge associated with the tall truss is its strong tendency to tip sideways, particularly in response to wind blowing perpendicular to the plane of the truss. This issue was addressed, in part, by linking the trusses together with longitudinal timbers—a ridge beam at the apex and five stout timbers, called roof plates. The designer also added diagonal braces between the roof plates and vertical posts.

- Beyond supporting the roof, the trusses were also integral to the cathedral's wind load–resisting system; thus, the truss supports had to be capable of carrying substantial horizontal forces in addition to the weight of the roof. To meet this demand, each support was augmented with a bracket assembly consisting of vertical, horizontal, and diagonal members supported on a stone projection, called a corbel.

- The roof trusses also provided support for the cranes that were used to build the vaults. To address this need, the tie beam was much thicker than would have been necessary just to resist the internal tension caused by the weight of the roof. Each tie beam was also reinforced by two supplemental hangers, each of which consisted of two parallel timbers, interconnected with oak pins. The upper two pins suspended the hanger from the collars, and the lower pin cradled the tie bar. This design prevented the tie beam from flexing excessively under construction loads.

- To ensure the system supported the roof, the designer added four assemblies called common rafters between adjacent trusses. Each common rafter consisted of two diagonals, three collars, and a base (called the sole)—but no tie beam. The common and principal rafters were all made of the same-sized timbers and were spaced only 2 feet apart; thus, they could directly support the roof planking, with no need for purlins or battens. The roof was covered with a waterproofing layer of lead sheeting, which was integrated with the gutters and drainage system.

- The design reflects a deliberate decision to use a large number of smaller timbers rather than a smaller number of larger ones. In the 13th century, deforestation had become a serious problem in much of Europe, and intensive forest management was already being practiced. Given that each individual rafter, tie beam, post, and brace in the Notre-Dame attic corresponded to a single tree, this structure required more than 1300 trees to build. In a managed forest, a 7-inch-diameter oak could be regenerated in about 50 years, while the 15-inch oaks used for the tie beams required upward of 400 years.

The medieval carpenter's favorite structural timber was oak, which is significantly stronger per pound than modern structural steel.

Byloke Hospital

- Byloke Hospital is a 13th-century infirmary that was part of a Cistercian abbey in Ghent, Belgium. Byloke is one of the most important early examples of the medieval timber-roofed hall—an architectural genre that would eventually become common in Flanders and England and would find its ultimate expression in the design of London's stunning Westminster Hall, constructed during the final decade of the 14th century.

- The roof of the hospital was built on stone walls that enclose a rectangular floorplan measuring 52 by 180 feet. Byloke's principal structural element is a heavy timber frame, which incorporates a great arch that spans across the hall and springs from stone corbels projecting from the walls.

- The 10 main frames are linked together by two pairs of roof plates and two purlins. These longitudinal members support closely spaced common rafters—each of which includes two diagonals, two collars, four soles, and thin bent boards, which stiffen the rafters while visually mimicking the arches of the main frames.

- Unfortunately, the master carpenter's decision to use timber arches rather than trusses to span the vast space proved to be problematic in the long term. Like all medieval hospitals, Byloke had to be sited near a water source; thus, it was built on poor-quality alluvial soil. Even though the

Byloke Abbey

stone walls incorporated robust buttresses, the combined effects of the arches' outward thrust and the soft ground caused the walls to tip outward over time. Only the timely installation of iron tie rods in the 17th century saved the structure—which has now been repurposed as a concert hall.

An especially important characteristic of Byloke's engineered system is its economical use of wood—achieved by using light, thin timbers for all members except the main frames. The two-tiered design concept was also extremely beneficial in this regard because it eliminated the need for long boards.

The Stave Church

The stave church is a Norwegian cultural icon and a masterpiece of medieval timber construction. The historical context for its development was the Christianization of Norway, which began in the mid-10th century but didn't really take hold until the mid-11th century, when the first permanent episcopal sees were established in the kingdom.

Norwegian kings and bishops were keen to emulate their counterparts in France and England by building great stone cathedrals in their cities. But rural Norwegians held fast to their Viking traditions and developed their own unique churches, applying a centuries-old Scandinavian building technique called stave construction to the architectural form of the Norman Romanesque basilica in an entirely original way.

Borgund stave church

In its earliest form, stave construction involved sinking timber posts deep into the ground, then connecting them with heavy wooden sills just above ground level. Tongue-and-groove planks—called staves—were then fitted together, inserted into a groove in the top of each sill, and capped with wall plates to create a stout, weatherproof enclosure. None of these early buildings have survived.

In the 12th century, builders started using stone foundations and thus achieved enough permanence to inspire the development of more sophisticated architectural concepts. By the early 14th century, about 1000 of these churches had been built. Today, only about 30 have survived. One well-preserved example is the Borgund stave church, built around 1200 in Lærdal, Norway.

- Built entirely of pine and without a single nail or bolt, the building's structural core is supported on four interlocking timber sills, positioned on a low stone foundation. The nave is defined by 12 cylindrical posts, which are mounted on sills interconnected with three sets of tie beams and capped with wall plates. Above the wall plates are five beautifully crafted roof trusses, which support a ridge beam, several sets of purlins, the roof planking, and an outer layer of wooden shingles. The trusses' steep pitch and heavy timbers reflect the extremely high snow loads to which Norwegian structures are routinely subjected.

- Withstanding high winds was a major concern in stave church construction. Builders addressed this concern with several types of structural augmentation:

  - Curved brackets added rigidity to the joints between posts and tie beams. Similar brackets were used to prevent the trusses from tipping sideways.

  - A belt of beautifully detailed cross bracing was extended around the full perimeter of the nave.

  - The external walls were augmented with diagonal bracing.

The decorative elements of the Borgund church—the multitiered spire, the dragonhead gables, the intricately carved portals—suggest that medieval Norwegians used their stave churches as repositories for the old Norse traditions that were rapidly being supplanted by a new Christian culture at the time.

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Roads and Bridges

As a technological entity, the land transportation infrastructure of the Middle Ages is often disparaged because it never achieved the technical quality or systematic character of the famous Roman road system. To some extent, this characterization is accurate; however, the simplistic view that all medieval roads were bad does a disservice to the medieval engineers who, over time, developed new approaches to the design and construction of transportation infrastructure—and ultimately surpassed Roman achievements in several important ways. This lecture looks at how medieval bridge builders used and adapted Roman systems to suit the unique needs of their time.

Roman Roads versus Medieval Roads

The vast Roman intercity road network was an extraordinary engineering achievement—as were the roads themselves. The typical Roman road was built by excavating several feet below the surface, then setting large stone blocks along both sides of the excavation to serve as curbs. The roadbed was built up from successive layers of large stones, smaller stones, and compacted gravel—a structure that provided high strength and good drainage. And on major, high-traffic roads, this base was then paved with large polygonal stone slabs, fitted together with great precision.

Roman road construction

Rome was able to build this superb road network not only because it had the resources and expertise to do so but also because the empire exerted control over the land traversed by the roads. Such was not the case in the turbulent, politically fragmented world of the early Middle Ages. Thus, during this era, merchants and travelers made do with what they had—the surviving Roman road network, augmented by an ad hoc patchwork of dirt tracks, crude cart paths, and the perimeter roads delineating the boundaries of farmers' fields.

- Like many other technologies, ground transportation took a giant leap forward during the Commercial Revolution of the High Middle Ages, when increased urbanization, manufacturing, and commerce drove substantially higher demand for the movement of agricultural products, raw materials, manufactured goods, and people.

- The development of two new pavement technologies enabled the construction of paved roads within towns and cities. Cobblestone roads were created by setting small, rounded stones (called cobbles) in a bed of mortar atop a base layer of sand—forming a surface that was hard and strong yet relatively flexible. And in regions where rounded cobbles weren't readily available, the same approach was used with flat stones, set on edge. The resulting surface is called a pitched pavement.

- The need to enhance the effectiveness of the existing ad hoc road networks was addressed not by improving the roads but by building bridges. And starting in the 11th century, bridge construction increased dramatically across Western Europe.

Widespread bridge construction has been characterized as "the great public work" of the Middle Ages. Ironically, even though most medieval bridge projects were initiated and funded locally, their aggregate effect was to create true national road networks—even if unintentionally.

Timber Bridges

- Most early medieval bridges were made of wood, but nearly all of the timber structures from the Middle Ages have been lost to rot, fire, and obsolescence. Two noteworthy survivors are the Spreuerbrücke and the Kapellbrücke—both of which are pedestrian bridges across the Reuss River in Lucerne, Switzerland.

- The first span of the Spreuerbrücke was constructed in the 13th century to connect the right bank of the Reuss with an island on which the city's grain mills were situated. In the late 14th century, three more spans were added to extend the bridge southward to the left bank of the Reuss. In 1566, these spans were badly damaged in a flood, but they were repaired and have been meticulously maintained since then. In the 19th century, the original 13th-century span was retrofitted with heavy-timber arches and thus has lost its medieval character.

Spreu is the German word for "chaff"—and the Spreuerbrücke got its name because the chaff from the milling process was tossed into the river from this bridge.

- Within the three surviving medieval spans, the principal structural elements are paired tie beam trusses, spanning distances of 37, 60, and 54 feet between the stone abutments and piers. The vertical members of the trusses serve as hangers, from which transverse floor beams are suspended. These beams support longitudinal timbers, called stringers, which work together with the truss tie beams to support the floor planks.

- The main trusses are also integrated with transverse frames, which hold the trusses in a vertical orientation while also incorporating the principal rafters of the roof system. These frames support longitudinal purlins, on which the closely spaced common rafters are mounted. The rafters and frames support the battens to which the wooden roof shingles are fastened. Additional longitudinal timbers support the outer walls.

- The Spreuerbrücke and its neighbor, the Kapellbrücke, are regarded as the world's oldest surviving truss bridges and thus are the distant ancestors of monumental modern trusses, such as the Betsy Ross Bridge in Philadelphia, Pennsylvania. One reason these medieval bridges have survived is that they're covered. The roof and walls help protect the principal structural elements from weather-related deterioration.

Stone Arch Bridges

- Beyond a few crude slab spans called clapper bridges, all surviving stone bridges from the Middle Ages are arches. An examination of the Elvet Bridge over the River Wear in Durham, England, will show how such bridges were made. Built between 1160 and the early 1200s, the Elvet was Durham's second bridge over the Wear, constructed to connect the city

Elvet Bridge

with the economically vibrant borough of Elvet, located just across the river. Its patron was Durham's powerful prince-bishop, Hugh de Puiset, who was renowned for his many building projects.

Scholars are not sure how many spans the Elvet Bridge has. It clearly has four spans across the River Wear, and six additional dry spans are at least partially visible on the approaches. But some historians and at least one historical marker claim that the bridge actually has 14 spans. If this claim is correct, then there are four massive stone arches completely buried beneath the outer ends of the approaches—lost to 8 centuries of encroaching urban development.

Construction and Function of Elvet Bridge

The first and most challenging phase of the construction project would have been building the piers that lie within the river channel. The usual approach was to build a cofferdam at each pier location, which involved driving two rings of closely spaced wooden piles into the riverbed, then packing clay into the space between the two rings to make the structure watertight. The water within the cofferdam was then pumped out—a task likely done by gangs of workers with buckets.

- Workers would then descend into the enclosure to excavate for the pier foundation, which involved digging down into the riverbed and removing sediment and poor-quality soil until a firm stratum was reached. The stone pier foundation was then laid on this surface, and upon this foundation, the pier was built with an outer facing of cut-stone masonry and an inner core of mortared rubble.

- One reason the piers have held up so well is their shape. Their pointed ends—called cutwaters—guide the flow of the river smoothly around the piers, thus reducing fluid pressure on the structure and preventing floating debris from accumulating on the upstream side.

- The process of constructing the arched spans was essentially the same as the one used to build the vaults of a cathedral. Timber centering was used to support each arch ring as it was being assembled. With the completion of each arch, the adjoining piers were extended upward, spandrel walls were erected above the arches, the intervening space was filled with mortared rubble, parapet walls were added, and then the roadway was surfaced with a cobblestone pavement.

Elvet Bridge was originally only 15 feet wide. In the 19th century, its width was increased by 18 feet on the upstream side. Today, evidence of the upgrade can be clearly seen beneath the arches.

- Multiple arches positioned end to end constitute an arcade—a configuration that is common in cathedrals and is advantageous because the outward thrust of each interior arch is counterbalanced by the thrust of the adjacent arches. In an arcade, only the outermost arches must receive external lateral support; for an arch bridge, this support is provided by heavy abutments built into the riverbanks.

- Unlike a cathedral's loading, which is static and distributed uniformly along the length of the arcade, an arch bridge must carry a loading that's both dynamic and nonuniform. For example, when a horse-drawn wagon loaded with building stone crosses a bridge, its entire weight is applied sequentially to each individual arch, and this concentrated load can be amplified if the wagon hits a bump in the road or another vehicle crosses in the opposite direction. This situation is dangerous because a concentrated load applied to one arch of an arcade increases the outward thrust of that arch alone, creating an imbalance in the lateral forces applied at the supporting piers. If this imbalance gets too large, it will cause a localized failure of the heavily loaded arch.

- The stability of the arches is maintained primarily by the spandrels, which stiffen the arch rings and increase the static weight of the bridge. Because this increased weight is uniformly applied to all the arches simultaneously, it increases their outward thrust uniformly; thus, the relative effect of the concentrated vehicular loading is reduced accordingly. And because the weight of the spandrels is centered over the piers, it significantly reduces the tendency of the arches to slide laterally in response to unbalanced thrusts.

Many medieval bridges received nonstructural additions—such as fortified gate towers, chapels, shops, and residential buildings—that were constructed directly on the bridge.

Engineering Innovations

- While the overall structural concept of medieval bridges was essentially the same as that of ancient Roman structures, medieval builders developed several structural enhancements that allowed for more flexibility in adapting a bridge to its local geologic, hydrologic, and economic conditions.

- For example, the pointed arches of the Elvet Bridge generate less outward thrust than semicircular arches of the same span—a feature that would be particularly important at sites where the geologic conditions weren't conducive to large horizontal support forces at the abutments.

In contrast, the arches of the Ponte Vecchio in Florence, Italy, are segmental, meaning that the shape of each arch is only a segment of a semicircle. For a given span, the rise of a segmental arch is less than that of a semicircular arch; consequently, its outward thrust is higher. There are two reasons why the designer would have used segmental arches for Ponte Vecchio:

- The low rise of the arches allowed for the construction of a level bridge deck at the same elevation as the local streets.
- For a given deck elevation, segmental arches allow for longer spans, which means fewer piers and, therefore, lower cost. More importantly, placing fewer piers within a river channel enhances navigability while also making the structure more resistant to flood damage.

Ponte Vecchio, Florence

Over time, medieval bridge engineers broke free from the constraints of the ancient Roman paradigm that relied almost exclusively on the use of semicircular arches. By breaking free from the rigid Roman approach, medieval bridge engineers were better able to adapt their designs to local conditions while also developing the confidence that enabled future innovations. This new spirit of adaptability in design represents a subtle but profoundly important advance in engineering practice.

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17

Monasteries: Tech Hubs of the Medieval World

This course has highlighted many examples of the outsized role that medieval monastic communities played in technological development—from their land-cultivation practices to their innovative uses of waterpower, such as the water-powered mill. The Cistercian order, in particular, was a major contributor to metallurgy and ironmaking technology. The Cistercians were also superb structural engineers, and, as this lecture shows, their monasteries were triumphs of architectural planning and hydraulic engineering. So, how did institutions that were founded for a purely spiritual purpose become the tech hubs of the medieval world? As this lecture will show, the monastic orders' propensity for technological innovation was deeply rooted in monasticism itself.

The Evolution of Christian Monasticism

- Practically from the start of Christianity, small numbers of men and women have chosen to isolate themselves from the secular world and live lives of prayer and self-denial. The earliest Christian monks were hermits, who lived alone in caves or crude huts in the Egyptian desert. Indeed, the word *monk* comes from the Greek *monachos*, which means "solitary." This form of monasticism, called eremitic, was essentially anti-technological.

- In the mid-4th century, an Egyptian monk named Pachomius created a new monastic paradigm—called cenobitic—in which the monks worshipped, worked, and ate communally in a facility (called a monastery), under the supervision of a leader (called an abbot), in compliance with a set of written regulations (called a rule).

- When monasticism spread to Western Europe in the late 4th century, there was no consensus on whether it should take the eremitic or cenobitic form. The issue wasn't decided until the 6th century, when Saint Benedict of Nursia established several cenobitic monasteries in Italy and wrote the *Rule of Saint Benedict*, which regulates every aspect of monastic life. And because his rule was so effective, it fostered the spread of Benedictine monasticism to most of Western Europe over the next 3 centuries.

- The precepts of Saint Benedict's rule include the following requirements for the monks:

  - to engage in communal prayer at eight specified times every day;
  - to sleep and dine communally;
  - to engage in manual labor;
  - to care for the sick and the elderly; and
  - to offer hospitality to guests and pilgrims.

The precepts of the Benedictine order substantially influenced the design of monasteries, and the requirement for self-sufficiency provided a powerful stimulus for the technological dimension of Western Christian monasticism.

The Plan of St. Gall

- As the Benedictine order grew, a two-tiered hierarchy of facilities also emerged. Large, autonomous monasteries led by abbots were called abbeys, and smaller ones were called priories. But the *Rule of Saint Benedict* didn't specify a standard architectural plan; thus, the design of early abbeys and priories varied widely, until the early 9th century, when the Carolingian kings—Charlemagne and his son, Louis the Pious—began advocating for greater uniformity in the practice of the faith.

- One product of this initiative was a document called the Plan of St. Gall, dated to around 820. Drawn on parchment and measuring approximately 44 by 30 inches, this is the only architectural drawing that has survived from the early Middle Ages. Since its creation, it has resided in the library of the Abbey of St. Gall in Switzerland—hence its name.

Abbey library of St. Gall

- Although some scholars disagree about its origin and purpose, the plan probably depicts the layout of an idealized Benedictine abbey, as determined by an early 9th-century conference of Carolingian bishops and abbots. It's unlikely that anyone ever intended to build this abbey; rather, the intent of the plan seems to be to illustrate an efficient arrangement of the various functional spaces required for compliance with the Rule of Saint Benedict.

- This masterplan organizes the abbey into four main zones. The most important is the abbey church—which is cruciform in plan, with the nave, chancel, and transepts intersecting at a central bay, called the crossing. At the west end of the church are two bell towers and a semicircular atrium.

- The second zone includes all the spaces in which the monks studied, worked, slept, and ate their communal meals. At its center is the cloister—a large, square courtyard enclosed by a covered passageway that provides access to the three surrounding structures—called the claustral buildings.

- The third zone includes all the industrial and agricultural facilities required to maintain the abbey's self-sufficiency. Among these are a water mill, granary, workshops, gardens, stables, and enclosures for livestock and poultry. To fulfill the abbey's obligation to provide hospitality, this zone also includes a house for pilgrims and paupers, guest quarters for elite visitors, and a school.

- The fourth zone is the infirmary, where the community cared for its aging and ill members. This zone was positioned far from the noisy activity of the agricultural and industrial areas.

- This architectural plan brilliantly addresses a major challenge that was confronting Benedictine monasticism at the time. By the 9th century, many monasteries had acquired so much agricultural land and so many industrial facilities that it was no longer possible for the resident monks to provide the labor needed to operate these enterprises. As a result, the monasteries employed large numbers of tenant farmers, serfs, servants, and other lay workers to perform these tasks. The challenge was that the incorporation of so many laymen into the community threatened to destroy the most fundamental aspect of monastic life—seclusion from the secular world. The plan addressed this challenge by reserving the cloister, the claustral buildings, and the eastern portion of the abbey church exclusively for the monks, effectively creating a monastery within a monastery.

The Plan of St. Gall successfully addressed the monasteries' competing demands of operating a monastery as an economic enterprise while also secluding its primary inhabitants from the outside world.

The Cistercian Order

- The Cistercian order was founded in 1098 at Cîteaux, France, by a group of monks who believed that the Benedictine order had grown too rich, too worldly, and too lax. These reformers sought to restore the purity and rigor of early medieval monasticism through "radical austerity" and strict observance of Saint Benedict's rule.
- The order also rejected the practice of operating monasteries as manorial estates. In lieu of employing lay workers, the Cistercians began admitting lay brothers, who were, in effect, lower-level monks. They took monastic vows, lived and ate within the abbey, and had specific obligations for daily prayer; however, the lay brothers spent most of their time working the farms, cooking meals, operating the abbey's industrial facilities, and performing other secular tasks.
- The office of lay brother proved to be quite popular and contributed significantly to the spectacular growth of the Cistercian order. By the mid-12th century, 300 Cistercian houses were operating in Europe, and by the year 1200, there were more than 500 such houses.

Rievaulx Abbey

- Rievaulx Abbey, in rural Yorkshire, England, was a typical Cistercian monastic complex of the High Middle Ages. It was founded in 1132 by a group of 12 monks, who journeyed from Clairvaux, France, with


Rievaulx Abbey

the mission of bringing Cistercian reform to northern England. By 1160, under the direction of a gifted abbot named Aelred, the Rievaulx community had grown to 140 monks and more than 500 lay brothers, who operated numerous farms and mills throughout the region.

Today, Rievaulx Abbey is a picturesque ruin—the sad result of the dissolution of England's monasteries by King Henry VIII after he broke with the Catholic Church in the 16th century.

The abbey was built on a west-facing hillside overlooking the Rye River. Initially, the main buildings were quite close to the river, but by the mid-12th century, the monks had diverted the channel about 500 feet westward to expand the pastureland within the abbey's 92-acre precinct. The original river channel was then reconfigured as a canal, with inflow controlled by a weir and a sluice gate. Eventually, this canal would supply water to a grain mill, a furnace, a tannery, a fulling mill, a fishpond, and a forge.

- Consistent with the Plan of St. Gall, Rievaulx's abbey church was cruciform in plan; however, because of the local terrain, the long axis of the church was oriented diagonally with respect to the cardinal directions. Thus, the chancel faced southeast rather than east. In such situations, it's customary to describe the locations of architectural features using "liturgical directions"—defined as if the chancel were facing due east.

- Consistent with the Cistercian ethic of austerity, the church's Norman Romanesque architecture was majestic but unadorned—with no sculptures, stained glass, or towers. The monks' cloister was positioned on the south side of the church. The monks merged the dormitory, dayroom, and refectory into a single integrated structure and provided more differentiation of the space within. The east range of the integrated claustral building incorporated not only the monks' dormitory and a dayroom but also a library, a parlor, a treasury, and the chapter house.

The Cistercians' balance of standardization and adaptation at Rievaulx reflects a level of planning expertise that's rarely seen elsewhere in the medieval world.

Rievaulx's Water System

- An important aspect of monastery design was water supply technology. The monks' daily routine required washing before meals, and water was essential for cooking, washing clothes, brewing beer, and conducting various religious rituals. Thus, monasteries were always sited near one or more sources of clean water, and many monasteries developed sophisticated systems for piping water directly from these sources to the functional spaces that needed it—and for disposing of wastewater.

- Very little of Rievaulx's water system survived the dissolution, but scholars have three useful sources of information about it: a medieval drawing of the abbey, which shows several external components of the system; the surviving ruins, which provide some tantalizing clues; and, most important, a detailed plan of the water distribution system that was installed in the priory of Canterbury Cathedral in the mid-12th century and thus is contemporary with the Rievaulx system.

- The water source for Canterbury's system was a series of springs located on the hillside above the abbey. Water from these springs was collected in a covered masonry tank, called a conduit house. From there, the water was channeled into the abbey's single water main. Based on the remains of a large-diameter pipe recovered from the ruins of a nearby monastery, it's likely that the Rievaulx water main was made of terra-cotta segments.

- Terra-cotta pipes aren't strong enough to withstand much internal pressure, so Rievaulx's water main must have operated by open-channel flow—meaning that the pipe was laid on a steady downhill gradient, and it flowed only partially full. In open-channel flow, the inside of the pipe remains at atmospheric pressure; thus, the water isn't subjecting the pipe to significant stress.

- The abbey's internal distribution system had to be pressurized to push water out to all the functional spaces that needed it. Thus, water from the main was dumped into a distribution tank located within the abbey complex, and smaller-diameter pipes ran from the bottom of the tank to various rooms. The weight of the column of water caused pressure in the distribution pipes.

- Lead pipes carried water from the distribution tank to holy water basins in the church and to a laver, located along the south wall of the cloister, just outside the refectory entrance. The laver had multiple basins—each with its own tap—and was used by the monks for handwashing and for ritual purposes. Other pipes supplied fresh water to the kitchens and probably the abbot's quarters.

- Wastewater was collected in a basin or trough, then channeled into a network of underground drains, which fed into a great drain that carried the accumulated effluent down the hillside to the canal. Today, the great drain is still visible where it emerges from beneath the infirmary. Several communal latrines were positioned directly above the great drain, so they could empty directly into it. The drain was also fitted with a sluice gate, which could be closed to build up a reservoir of water, then opened to flush out the solid waste.

To maintain the monastery's economic self-sufficiency without neglecting their spiritual responsibilities, monks developed technologies that increased productivity or reduced the need for human labor. The institution had not only the intellectual horsepower needed to create these technologies but also the leadership and the resources to translate good ideas into reality. As a result, medieval monasteries became engines of technological development that materially improved the human condition during the medieval era—and beyond.

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18

Brunelleschi's Dome

This lecture, which concludes the set on medieval structural engineering and architecture, examines one of the world's most magnificent structures—the dome of the Cathedral of Santa Maria del Fiore in Florence, Italy. Designed by the great Florentine architect-engineer Filippo Brunelleschi, this 15th-century icon of the Italian Renaissance was constructed atop a great Gothic basilica that was begun more than a century earlier. Thus, Brunelleschi's dome is firmly rooted in the Middle Ages; yet, as a product of the Renaissance, it also reflects the emergence of a new architectural style and a fundamentally new approach to engineering design. Brunelleschi's dome is also worth studying because it is an architectural masterpiece that's physically, culturally, and spiritually intertwined with the place and time of its creation.

Building the Cathedral

- By 1294, the Florentine economy was booming—due to the success of its textile and banking industries—and a recent series of ordinances had affirmed Florence's political status as an autonomous republic, governed by representatives of the city's guilds. In that year, as an expression of growing civic pride, the city's ruling council approved the construction of a new cathedral.

- Named Santa Maria del Fiore (Our Lady of the Flower), the cathedral was designed by the Tuscan architect Arnolfo di Cambio. His design was Italian Gothic in style, cruciform in plan, and conventional in all respects but one: the crossing would be covered by an immense octagonal dome. With a span of 134 feet, this dome would be second in size only to the ancient Roman Pantheon, but it would be far more challenging to build because of its elevated position, more than 100 feet above the floor. Despite these unprecedented specifications, di Cambio provided no guidance on how this great dome was to be built.

- Construction of the cathedral began in 1296, but after di Cambio's death during the following decade, the project languished, stopping for extended periods of time. In the early 1330s, supervisory responsibility for the project was assigned to the Opera di Santa Maria del Fiore—a council composed of members drawn from the city's wool guild. In Italian, the word *opera* means "work"; thus, the council was the supervisor of works for the cathedral.

- In 1334, the Opera hired a new master builder—the painter Giotto—who designed the cathedral's elegant Gothic bell tower but died before it could be completed. In the 1350s, a new master builder, Francesco Talenti, decided to enlarge the cathedral substantially, even though construction was already well underway. And a decade later, the Opera became embroiled in a controversy over whether to retain the Gothic buttresses and pinnacles envisioned by di Cambio or to adopt the classical style, which was becoming increasingly popular at the time.

Santa Maria del Fiore

In 1367, the Opera convened a board of experts to resolve this controversy and prepare a final plan for the cathedral. Ultimately, the board opted for a classical design, then had the citizens of Florence ratify this decision through a popular referendum. For both its architectural and political implications, this decision was one of the most important milestones of the early Italian Renaissance. But because classical architecture emphatically rejected the use of Gothic-style buttresses, the challenge of supporting the dome remained.

Filippo Brunelleschi's Proposal

As the 15th century dawned, the century-old cathedral was nearing completion, yet there was still no plan for building the dome. In a 1407 consultation with the Opera, an architect-engineer named Filippo Brunelleschi recommended the construction of a 30-foot-tall octagonal drum over the crossing. He argued, correctly, that the drum would help direct the dome's weight more uniformly downward into the four main piers of the crossing. The Opera accepted his recommendation, and construction of the drum began.

- By 1418, the drum was nearing completion, and the Opera initiated a public competition for the design and construction plan for the dome. In response, Brunelleschi and his chief rival, Lorenzo Ghiberti, both submitted designs, but Brunelleschi shocked the judges by claiming he could build his dome—largely of brick—without using temporary centering to support the masonry during the construction process. Such centering would have required an impossibly large quantity of wood and would also have greatly impeded the construction process by filling the entire space below the dome with a forest of posts and bracing.

To ease his critics' concerns about the construction of a major domed structure without centering—which had never been attempted—Brunelleschi presented a large-scale model of his proposed dome, using more than 5000 bricks.

- In 1420, the Opera finally settled on Brunelleschi's design. However, because they were still skeptical about the plan, they directed that supervisory responsibility for construction was to be shared by Brunelleschi, Ghiberti, and Battista d'Antonio—an experienced master mason. However, Brunelleschi convinced the Opera to let him lead the project, and he became the de facto chief architect, chief engineer, and construction superintendent.

Major Challenges of the Dome's Design

- In designing the dome of Santa Maria del Fiore, Brunelleschi was confronted with four major challenges. First, all domes experience circumferential tension under load. And if a dome is made of brick, it will develop meridional cracks and will effectively become a series of discrete arches arranged around a vertical axis. The outward thrust generated by these arches must be restrained, or the dome will collapse.

Dome of Santa Maria del Fiore

- This vulnerability was greatly exacerbated because the dome's thrust would cause the walls of the drum to tip outward. This tendency could have been prevented by using heavy Gothic-style buttresses, but the Opera had rejected this solution on aesthetic grounds. Thus, the dual challenge of circumferential tension and outward thrust would need to be addressed with a design solution that was internal to the dome.

- Brunelleschi's second challenge was to build the dome without using temporary centering. The bricks would be laid on beds of mortar, and the associated bedding plains would slope inward at progressively steeper angles with increasing elevation. During construction, the bricks would have to be prevented from sliding off the wet mortar and falling into the void, and the dome's shape would have to be maintained long enough for the mortar to harden.

- The third challenge was to account for the dome's octagonal plan. The flat sides tend to sag inward—particularly during construction—and the corners cause major concentrations of internal stress, which could significantly compromise the dome's structural integrity.

- Brunelleschi's fourth challenge was to ensure that the dome could support not only its own weight but also the weight of a stone lantern—which would weigh 37 tons—placed at its peak.

Design Features to Address Challenges

The Pointed Fifth and Double Shell

- To address the dome's unique challenges, Brunelleschi incorporated six major design features—five of which were unprecedented innovations. The least innovative of them was the dome's tall profile. Its shape is called a pointed fifth because it's constructed by drawing two arcs from the centers of curvature located at one-fifth of the span, measured from each end. A pointed arch or dome generates significantly less outward thrust than its semicircular equivalent, and the pointed-fifth profile would be better suited for supporting the concentrated weight of the stone lantern. This profile was also an essential enabler for Brunelleschi's scheme to build the dome without centering.

Despite the fact that Renaissance architects had rejected the Gothic-style pointed arches in favor of semicircular arches, Brunelleschi clearly recognized that structural concerns outweighed aesthetic preferences when designing the dome.

- Brunelleschi's second design feature was to configure the dome as two concentric shells: a thick inner shell and a thin outer shell, with a 4-foot-wide cavity in between. To ensure that the shells functioned as a single structural entity, they were interconnected by a solid stone base, an octagonal oculus ring (or keystone) at the top, and 24 radial ribs—8 at the corners and 2 within each side of the octagon. The corners were also reinforced by external ribs.

- The resulting structure is quite rigid but significantly lighter than a single-shell dome would have been; thus, it experiences less circumferential tension. The double-shell configuration also facilitated construction by providing a space for internal stairways and circumferential walkways at three levels.

A climb to the summit of Brunelleschi's dome will be the highlight of any traveler's visit to Florence.

Circumferential Chains and Internal Half Arches

- To further reduce the dome's circumferential tension, Brunelleschi's third design feature included four circumferential chains embedded within the dome. Three were made of stone, and one was made of wood. These elements strengthen a dome by stretching (in tension) as the dome bulges outward under load. And if they're strong enough, the dome requires no external lateral restraint.

- Each of the stone chains was configured like a set of railroad tracks, with two concentric octagonal rings supported on transverse ties. All these elements were composed of sandstone blocks connected by wrought iron clamps. When the dome was built, these chains were embedded within the surrounding masonry; thus, they're largely hidden from view.

- Brunelleschi's single wooden chain seems to have been added as a backup. This chain is a ring of heavy chestnut timbers, connected with oak splices and iron bands and pins. Hardwood is significantly stronger in tension than sandstone; however, it's also much more flexible, so the wooden chain would have to stretch quite a bit before it could develop enough internal tension to resist the dome's outward thrust. Thus, it couldn't prevent the dome from cracking—but it might help prevent a collapse if the stone chains failed. Modern engineers call this approach a belt-and-suspenders design.

- Because an octagonal dome's flat sides tend to sag inward under their own weight, Brunelleschi's fourth design innovation was to add internal half arches, which span between the corner ribs and the intermediate ribs and are integral with the outer shell.

Interior of the dome of Santa Maria del Fiore

Specialized Techniques for Laying Brick

- Brunelleschi's fifth innovation involved a brilliant geometric scheme for laying courses of brick in his dome. The bedding surfaces on which the bricks were being laid were not flat—each one sagged slightly between adjacent corners of the octagon. Brunelleschi called it the slack-line method because the curve resembled the shape of a rope or chain suspended between two supports.


Brickwork of the dome of Santa Maria del Fiore

- The eight curved bedding surfaces were, in fact, a single surface, defined by intersecting the octagonal dome with an inverted circular cone. By defining the surfaces this way, sharp discontinuities at the corners disappeared, which reduced dangerous concentrations of internal stress.

- Brunelleschi's sixth design innovation was to use a herringbone brick pattern—his principal mechanism for building the dome without centering. The bricks were laid in groupings of four horizontal bricks and one vertical brick, placed in successive courses that were shifted laterally by the thickness of one brick.

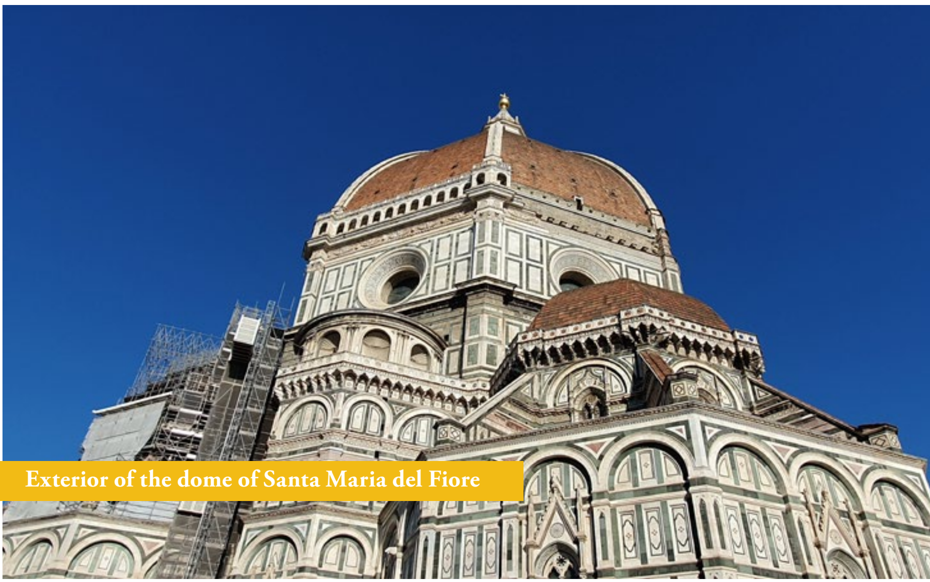
- The herringbone brick pattern causes the upper bedding surface to be punctuated by the ridges of vertical bricks, which prevent the next group of bricks from sliding inward. Furthermore, once the grouping is locked in position, it will support additional bricks placed above it.

- The great dome was structurally complete by 1436, and construction of the lantern had just begun when Brunelleschi died in 1446. The lantern was completed—to his specifications—25 years later.

In recognition of his contributions to Florence, Brunelleschi was buried in Santa Maria del Fiore, and a statue of the master—drawings in hand, looking intently upward at his dome—was erected in the cathedral square.

Brilliant but Not Flawless

- Shortly after it was completed, the dome started experiencing severe structural distress. Large, vertical cracks formed in four of the dome's eight sides, and over time, they grew downward through the drum and upward to approximately two-thirds of the dome's height. Today, these fissures are 1 to 2 inches wide, and they extend through the full thickness of the masonry—meaning that all three of the stone chains must have fractured.



Exterior of the dome of Santa Maria del Fiore

- Modern structural analyses have confirmed that the cracks were caused by circumferential tension due to the dome's 32,000-ton weight. From this failure, one can conclude that Brunelleschi's design was deeply flawed in his use of sandstone chains.

The outward thrust of the cracked dome is now being carried primarily by outward bending of the drum walls and possibly by the wooden chain, which is probably still intact. The dome's survival is a tribute to other aspects of Brunelleschi's design—especially the reduced outward thrust resulting from the dome's tall profile and its lightweight double-shell construction.

Brunelleschi's dome represents a key turning point in the history of engineering. Earlier monumental structures were designed empirically and incrementally, using multiple iterations to make small improvements over previous successful designs. But the challenges Brunelleschi faced were so unprecedented that such an approach wasn't an option. He had to develop his design conceptually, by applying reason and a deep qualitative understanding of structural behavior. In this sense, Brunelleschi took a small but important step toward the modern approach to engineering design.

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19

Marvelous Medieval Machinery

This course has highlighted numerous important medieval machines, including the heavy plow, counterbalance loom, waterwheel, drawbridge, and trebuchet. Along the way, many lectures have also touched on important mechanical functions—such as lifting construction materials, driving piles, and many mechanical applications of waterpower. This lecture explores some of those functions more deeply and considers two important medieval technological trends: a growing recognition of the range of tasks that could be performed by machines and an ever-greater ingenuity in the design and construction of these devices. These trends began with the Commercial Revolution, accelerated during the late medieval period, and ultimately came to full fruition in the Industrial Revolution of the 18th century.

A Conceptual Leap

A machine is an assemblage of parts that work together to perform a desired task.

- From antiquity through the early Middle Ages, grinding grain was the default application of waterpower, not only because performing this task manually was onerous and time-consuming but also because producing mechanical power (with a waterwheel) and grinding grain (with a spinning millstone) both involved rotary motion and thus were mechanically compatible.

- By 1500, waterpower was being used as the prime mover for an astonishing range of industrial applications. A significant factor in this explosion was medieval engineers' embrace of the camshaft—a mechanism that converts rotary motion into reciprocal (back-and-forth) motion by the action of one or more cams mounted on a rotating shaft. A cam is a post or lobe that moves another mechanical component repetitively as the shaft rotates.

- It had taken a major conceptual leap for engineers to recognize that tasks requiring reciprocal motion could be accomplished by a continuously rotating shaft. This leap was prompted by and implemented through the camshaft, and the result was a great awakening to all sorts of new possibilities for mechanization.

The Trip-Hammer

- The earliest and most common application of the camshaft was the trip-hammer, which could be used for any task involving repetitive pounding. The earliest documented use of trip-hammers in Europe is in the 11th century, though they were probably in use much earlier.

- One type of trip-hammer—called a vertical stamp—was so named because the hammer slides vertically in its wooden frame. With each rotation of the camshaft, the cam engages with a projecting lug on the hammer, raises the hammer a few inches, and then drops it as the cam rotates out of

Trip-hammer

contact with the lug. Vertical stamps were often used for crushing ore and pounding the stalks of hemp and flax to obtain fibers for making rope and linen thread.

- An alternative configuration was the recumbent trip-hammer, which was oriented horizontally and pivoted on a hinge. This machine used the principle of the lever to amplify the impact energy of the hammer. It was often used for forging iron, probably because its motion replicated that of a handheld blacksmith's hammer.

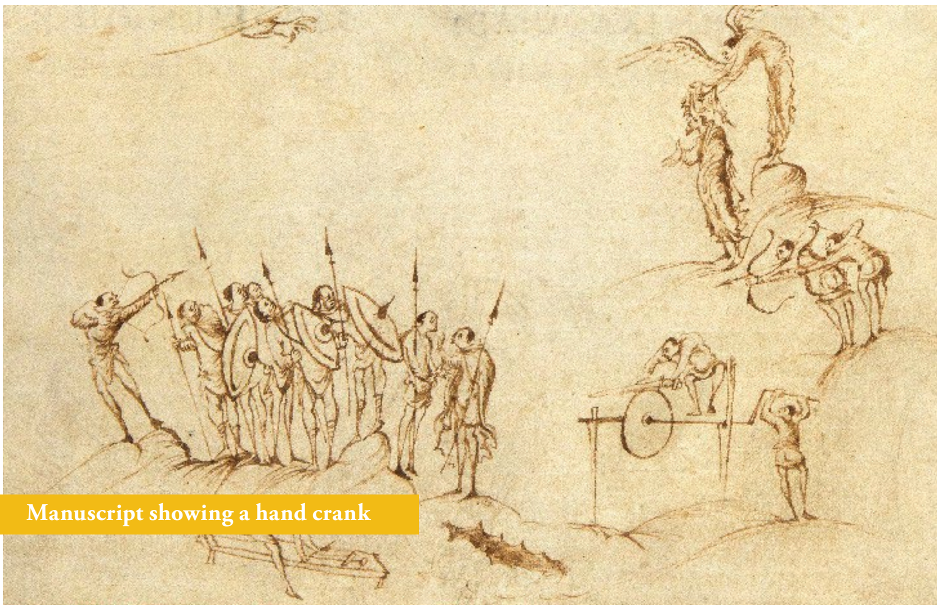
- Once camshafts came into widespread use for driving trip-hammers, it was only a matter of time before this technology was applied to other types of reciprocating machinery—including piston pumps, which were used to drain water from mines, and bellows that supplied air to furnaces and forges.

- A major limitation of the camshaft is that a cam can move a machine component in only one direction. To achieve reciprocal motion, the camshaft requires increased mechanical complexity. This limitation wasn't addressed until the late 15th century, when the crank and pushrod came into use.

A particularly astute use of camshaft technology was its use with furnaces. A waterwheel-driven camshaft would trigger two sets of bellows sequentially to produce a continuous blast of air into the furnace. This application was probably the world's first use of mechanical programming—which is used today in applications such as the camshaft that opens and closes the valves in an internal combustion engine.

The Crank and Pushrod

- In its simplest form, a crank uses a handle that's offset from, but attached to, a rotating shaft to produce rotary motion by alternately pulling and pushing the handle. The origins of this device are uncertain. In medieval Europe, the earliest representation of a crank is a 9th-century drawing of a grindstone being used to sharpen a sword. Europeans found many creative new uses for the crank—including windlasses for lifting construction materials, a musical instrument called the hurdy-gurdy, and winches for spanning crossbows.



Manuscript showing a hand crank

- The crank wasn't used in industrial machinery until it was paired with the pushrod in the late 15th century. The crank and pushrod is superior to the camshaft in two ways. First, the crank drives the pushrod in both directions—forward and back. And second, a crank and pushrod can be operated in reverse; that is, it can be used to convert reciprocal motion into rotary motion. This latter advantage is the basis for the treadle-powered spinning wheel—which converts the reciprocating motion of the foot-powered treadle into the continuous rotary motion of the wheel.

- Typical industrial applications of the crank and pushrod include a late 15th-century water-powered sawmill, which moved the reciprocating saw blade without the aid of counterweights or springs, and an incredible two-stage pump, which was used to remove water from mines.

Treadwheel Cranes

- Despite the astonishing variety of innovative waterpower applications that were in use by the end of the medieval era, human- and animal-powered machines remained quite common. They, too, underwent innovations, particularly during the late Middle Ages. An example of one such machine is the construction crane.

- On medieval construction sites, there was a near-constant need to move stone, brick, mortar, and timber from ground level up to the locations where these materials were being installed. Over the course of the Middle Ages, this need was met first by manual laborers carrying materials on hods or stretchers, then by simple hand-operated windlasses, and, starting in the early 13th century, by high-capacity treadwheel cranes.

- Configurations varied widely, but all treadwheel cranes used the same power source—one or two people walking inside a spoked wooden wheel rotating on a wooden axle. The wheel was about 15 feet in diameter and 4 to 5 feet wide, with treads attached to the inside of the rim. The lifting rope extended from the wheel shaft up through a pulley that was suspended from the end of a wooden boom, then down to the load. As the operator trod the wheel, its rotation wound the rope around the wheel shaft and lifted the load.

- When a treadwheel crane was used to build the vaulting of a cathedral, it was typically positioned within the attic, where it could be supported by the heavy tie beams of the roof structure. But in circumstances where the heavy treadwheel couldn't be safely supported aloft, it was placed at ground level, and only the boom and pulley were positioned aloft.

- The lifting force (*F*) generated by this machine can be calculated as the operators' weight (*W*) multiplied by the horizontal distance (*d*) between their center of gravity and the wheel's axis of rotation, divided by the axle radius (*r*): $F = Wd / r$.

A typical medieval treadwheel operated by two 150-pound men could lift about 3000 pounds—a mechanical advantage of 10 to 1. Given that the heaviest stone blocks used in Gothic cathedrals rarely weighed more than 1 ton, this crane provided more than enough capacity for routine construction tasks.

- The standard treadwheel crane wasn't sufficient for Filippo Brunelleschi's extraordinary dome in Florence. To lift significantly heavier loads to a greater height with better operational efficiency, he designed an animal-

Double drum squirrel cage

powered, three-speed, reversible, high-capacity winch—called the great hoist by his contemporaries. Its highest-capacity shaft had a theoretical mechanical advantage of 36:1 and could have easily lifted 30 tons.

- Scholars know about Brunelleschi's great hoist only because it was sketched by several of his colleagues—including the gifted Sienese artist-engineer Mariano Taccola. After Brunelleschi died, the innovative engineering concepts embodied in his hoist—and in his other beautifully designed lifting devices—were never adopted by later Renaissance engineers, who instead adopted the ancient Roman cranes described by Vitruvius.

Pile Drivers

- From antiquity until the invention of the steam-powered pile driver in the 1800s, the process for driving a pile entailed raising a heavy weight, dropping it onto the head of a pile, and then repeating this process until the pile was firmly embedded in the ground. The two mechanical challenges inherent in this process were lifting the weight and controlling it during the drop.

- The simplest solution to these challenges was the hand ram—an example of which would be the use of a large tree stump to hammer a pile into a riverbed. For bigger jobs, builders developed a device that provided more impact energy by dropping a heavier ram through a larger vertical distance. Simply called an engin in medieval sources, this pile driver consisted of an iron ram suspended from a wooden frame that incorporated two vertical guides to control the fall of the ram. A lifting rope was routed from the ram through a pulley at the top of the frame and back down to ground level, where it was subdivided into multiple pulling ropes operated by a gang of workers.

- Engineers inevitably sought to improve the engin by adding a windlass, which would provide mechanical advantage to assist with raising the ram. Yet, this enhancement created a new challenge—the need for a release mechanism that would allow the ram to fall freely, without causing the windlass to unwind uncontrollably.

An ingenious solution to this challenge was published around 1450 by Mariano Taccola, the same Renaissance engineer who sketched Brunelleschi's great hoist. In Taccola's pile driver design, the ram was lifted by a large iron hook, which was suspended from a pivoting yoke at its center and incorporated a long lever with a roller at its outer end. The ram was raised by a windlass, which pulled the lifting rope through a pulley at the top of the wooden frame. As the hook ascended, the roller struck a cross member, and the resulting rotation of the hook released the ram. Guideposts ensured that the ram struck the pile squarely and remained in the proper position to initiate the next blow. Taccola's design also included a second lifting hook. Both hooks were rigged to the windlass with a single rope, which raised one hook as it lowered the other.

Despite the existence of Taccola's sophisticated machine—a product of Renaissance-era inventiveness—the brute-force approach of the hand ram continued to be used. Nonetheless, by the end of the Middle Ages, the trend toward ever-greater mechanization had become part of the Western worldview, and even if the pioneering work of Brunelleschi and Taccola didn't significantly influence machine design in the short term, it would profoundly inspire the innovators of future generations.

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The Verge-and-Foliot Clock

From a 21st-century perspective, it's difficult for one to grasp the extent to which the invention of the mechanical clock in the late 13th century changed how people experienced day-to-day life. Its development was a major contributor to the late medieval trend toward increased mechanization, and it laid the foundation for the development of high-precision timepieces, without which the Scientific Revolution could never have happened. Although the origins of the mechanical clock remain uncertain, the technology itself is well understood because many examples can still be found in churches, town halls, and museums all over Europe. This lecture explores the mechanism at the heart of this invention—the verge escapement—a technological marvel that changed the meaning of time itself.

Sundials and Water Clocks

- From antiquity through the High Middle Ages, the time of day was determined primarily by sundials, which used a cast shadow to indicate the hour of day. Each day was divided into 12 hours of daylight and 12 hours of darkness, even though the total length of daylight and darkness in a given 24-hour period changed throughout the year. Thus, the hour was a variable quantity—varying not only between daytime and nighttime but also with the time of year and geographic location.

- The invention of the mechanical clock made it possible—indeed, necessary—to subdivide each day into 24 equal units of time, thus changing the hour from a variable quantity to a fixed time period. In this way, the mechanical clock fundamentally changed humans' conception of time, as their lives were no longer regulated by the rising and setting of the sun but rather by the ticking clock.

- Another principal timekeeping technology that preceded the mechanical clock was the water clock—which used the flow of water into or out of a vessel to measure the passage of time. The typical ancient water clock was a ceramic bowl with a precisely calibrated hole in its bottom. The bowl was filled with water, and the time required for it to flow out through the hole was used as a standardized interval of time. Called a clepsydra (from the Greek term *klepsydra*, meaning "water thief"), the ancient Greeks used this device to allot time for defendants to plead their cases in law courts.

- The clepsydra was widely used because of its simplicity; however, its usefulness was limited by its dependence on waterpower. Water flows from the bottom of a reservoir at a velocity equal to the square root of $2gh$, where g is the acceleration of gravity and h is the head—the vertical distance measured from the outlet to the surface of the water. Thus, for a device like the clepsydra, the rate of outflow is not constant; as h decreases, v decreases—that is, as the water level falls, the flow diminishes. Because of this limitation, the clepsydra was significantly less useful for tracking the time of day than for measuring a specific interval of time.

Sundial on St. Mary's, Thornbury

- In the 3rd century BC, this limitation was addressed by an inventor named Ctesibius, who developed a two-reservoir water clock. Outflow from the upper reservoir gradually filled the lower reservoir, in which a floating pointer was used to indicate the hour of day. The head of the upper reservoir was kept constant by providing enough inflow to keep it continuously overflowing; thus, the flow into the lower reservoir remained steady. This ingenious device also incorporated a rotating variable time scale to accommodate the varying lengths of hours throughout the year—long in the summer, short in the winter.

- In later centuries, this and similar approaches allowed for the development of increasingly sophisticated water-powered clocks and other mechanisms—especially by Arab clockmakers, who incorporated elaborate geared mechanisms that sounded bells, indicated the positions of the heavenly bodies, and propelled mechanical figures.

- Water-powered clocks were still subject to significant practical limitations: They required an ample water supply and drains for the overflow, their reservoirs had to be periodically emptied or refilled, their accuracy could be drastically reduced by clogging or corrosion of the outlets, and they didn't work in freezing weather.

The Verge Escapement

- By the late 13th century, European craftsmen were attempting to design clocks driven by falling weights rather than flowing water. But it would take several decades for designers to solve the problem of regulating the fall of the weight. This problem was eventually solved, though scholars don't know where, when, or by whom. Unambiguous references to weight-driven clocks appeared in the early 1300s.

Scholars are unsure about why the mechanical clock was originally developed. A common explanation is that monasteries needed an instrument that could determine the times of daily prayers more accurately and reliably. Other scholars claim that it was developed to satisfy merchants' demands for more accurate timekeeping or astrologers' needs to predict the movements of the sun, moon, and planets with greater precision.

- All first-generation mechanical clocks were powered by a weight that was suspended from a rope wrapped around a rotating drum. While this choice was logical in some ways, it was also problematic because a freely falling weight accelerates—its velocity increases continually with time—and if the weight is being used to drive the rotation of a clock mechanism at a constant speed, acceleration is a big problem. This challenge was addressed with a device called a verge escapement.

- The escapement is composed of three main mechanical components, all forged from wrought iron. The first component is called the crown wheel—a toothed wheel that is fastened to the same shaft as the drum; thus, as the weight falls, the wheel will rotate. While the number of teeth can vary considerably, the number must be odd.

Mechanical clocks were the world's first machines made entirely of iron.

Wells clock

- The second component is the verge—a vertical rod on which two appendages, called pallets, are mounted. The pallets are perpendicular to each other, and their longitudinal spacing corresponds to the diameter of the crown wheel.

- The third component is a horizontal bar—called the foliot—fixed to the top of the verge. The T-shaped assembly is then mounted on bearings within the wrought iron frame, and the pallets are engaged with the crown wheel teeth. Because the verge-and-foliot must be free to rotate with as little friction as possible, the upper end of the assembly is suspended from the frame with a short length of wire.

- Finally, two weights are hung from the foliot to provide the machine with adjustability. The falling weight rotates the crown wheel, which drives the pallets of the verge in opposite directions. This rotation is periodically stopped by the alternating contacts between the pallets of the verge and the wheel's upper and lower teeth. These contacts are responsible for the clock's characteristic ticktock sound.

- Each oscillation of the verge-and-foliot consists of the following sequence of events. First, an upper tooth of the crown wheel strikes the top pallet, causing the verge to rotate. But this rotation also moves the top pallet out of contact with the tooth, thus allowing the crown wheel to jump forward, or "escape." After this brief period of free rotation, one of the crown wheel's lower teeth is caught by the bottom pallet. Because the lower and upper teeth are moving in opposite directions, this contact stops the rotation of the verge and then pushes it back in the opposite direction. As the bottom pallet rotates out of contact with the crown wheel, the wheel again "escapes" until it's caught by the upper pallet—and a new oscillation begins.

- The most important characteristic of this mechanism is that the shape of the crown wheel's teeth and the orientation of the pallets ensure that the wheel can only advance by one tooth for each full oscillation of the verge-and-foliot.

- In a verge escapement, the weight still accelerates but only during the escapes—the time intervals when the pallets are not in contact with the crown wheel. During each contact—that is, each tick and tock—the verge stops and briefly reverses the fall of the weight, then releases it for another interval of acceleration. Thus, the escapement operates by subdividing the fall of the weight into a series of discrete time intervals of equal duration. The duration of one such interval is called the period of the escapement.

The Verge-and-Foliot Clock

- The unknown artisans who invented the verge-and-foliot clock automated the process of counting oscillations by adding gears to drive a pointer that completed one full rotation in either 12 or 24 hours. Today, this pointer is known as the hour hand. However, the earliest mechanical timekeeping devices had neither hands nor clockfaces; rather, they simply sounded an alarm, which notified a human operator to ring the church bell manually. Around 1335, clockmakers added a mechanism that rang the bell automatically, and by the end of the century, the more familiar fixed dial and rotating hour hand had become the standard convention.

To transform an escapement into a functional clock, a medieval clockmaker would have designed a gearset—a pair of meshed gears, each fixed to its own rotating shaft. A gearset always includes a driving gear, which receives mechanical power through its shaft, and a driven gear, which transmits this power onward to another part of the machine. If a small-diameter gear drives a larger one, then the gearset increases the torque applied to the driven shaft but reduces its speed. If a larger gear drives a smaller one, the gearset increases the speed of the driven shaft but reduces its torque.

Prague astronomical clock

- The most important engineering property of a gearset is the gear ratio, which is defined as the number of teeth in the driven gear divided by the number of teeth in the driving gear. For example, a gearset consisting of a 10-tooth gear driving a 30-tooth gear has a gear ratio of 3 to 1, or 3. Such a gearset would increase the torque applied to the driven shaft by a factor of 3 but would reduce its speed by the same amount. And if the gearset was run backward, its gear ratio would be 1 to 3, or one-third, and it would increase speed but reduce torque by a factor of 3.

- Medieval clocks typically used gearsets consisting of small lantern pinions driving larger spur gears—gears in which the teeth lie in the same plane as the gear itself. A lantern pinion should generally have at least six teeth, or the gearset will be susceptible to jamming.

- To achieve the required speed reduction while also avoiding impractically large driven gears, medieval clockmakers used a compound gearset—a system of gears in which one or more shafts have both a driving gear and a driven gear mounted on the same shaft.

- In terms of accuracy, the medieval verge-and-foliot clock typically gained or lost upwards of 30 minutes over a 24-hour period and had to be reset at least once every day, using the most ancient of all timekeeping technologies—the sundial. This relatively poor accuracy resulted from inherent variability in the operation of the verge escapement—an issue that wasn't addressed until Christiaan Huygens invented the pendulum clock in the 17th century.

The verge-and foliot clocks weren't accurate enough to justify the measurement of minutes and, therefore, never used minute hands—which wouldn't be invented until the late 16th century.

- Despite its limited accuracy, the verge-and-foliot clock changed the face of Europe. In 1370, only about 30 of these machines were in use, but just a few decades later, they were a common feature of the urban landscape. Mechanical clocks soon became objects of civic pride and prestige, leading to the addition of many features—both practical and fanciful—beyond mere timekeeping.

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21

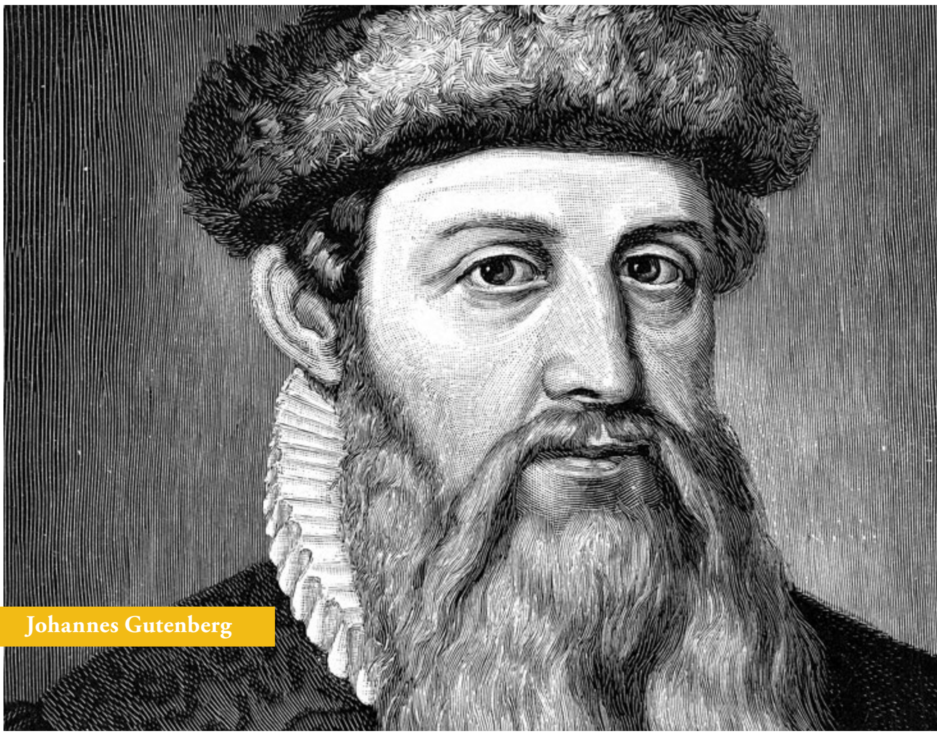
Gutenberg and the Printing Press

Before Johannes Gutenberg, nearly all European books were handwritten by scribes, who copied existing texts by writing with quill pens on parchment. This bookmaking process was slow, labor-intensive, and plagued by inaccuracy and nonuniformity. And because hand-copied texts were necessarily limited in quantity, literacy was largely confined to members of the clergy and the few laymen who could afford to buy books. Gutenberg's invention changed everything. His mechanical printing system—which consisted of several integrated technologies and processes—could produce high-quality texts faster and in larger quantities than the traditional hand-copying process. The result was an information revolution that contributed immeasurably to the Italian Renaissance, the Protestant Reformation, the Scientific Revolution, and virtually all technological development from that point forward.

Johannes Gutenberg

- The man known today as Johannes Gutenberg originally went by the name Johannes Gensfleisch zur Laden zum Gutenberg. In his time, members of noble German families often appended the name of their current residence to their surname, and Gutenberg was the name of his family's estate in Mainz, Germany.

- Gutenberg was born in Mainz around 1400. His father, Friele Gensfleisch, was a prosperous cloth merchant who also served as an official of the local mint. Friele's wife, Else, was a commoner, whose low birth would prevent her son from achieving the same elite status held by his father. Gutenberg would have to rely on his own wits, rather than aristocratic privilege, to succeed.



Johannes Gutenberg

- In the early 1430s, Gutenberg moved to the city of Strasbourg, where he remained for at least a decade. There, he worked as a goldsmith, while also attempting to raise capital for a highly secretive project—which, records suggest, was the development of printing with movable type.
- His pursuit of this technology coincided with an inexorably growing market for printed works. When church scribes could no longer keep pace with the demand, private copyist businesses sprang up and quickly became profitable. In this environment, the economic potential of mechanized printing was enormous—and Gutenberg knew it.
- By 1448, he was back in Mainz, where he converted the old Gutenberg residence into a printing workshop. Two years later, he received a sizable loan from a wealthy businessman named Johann Fust and began printing simple, experimental products. It would take Gutenberg another 5 years to produce his signature work—the Gutenberg Bible—but this masterpiece would secure his legacy as the inventor of the printing press.

The claim that Gutenberg invented the printing press is deceptive. It's more accurate to characterize his achievement as a creative synthesis of existing technologies that had been in use long before he was born. Nonetheless, it was a work of genius—the spectacularly successful product of Gutenberg's unique experience, ingenuity, and dogged determination to overcome the many challenges he encountered along the way.

Paper and Ink

- The technological system Gutenberg developed, now called letterpress printing, incorporated four main components—paper, ink, movable type, and the mechanical press—which he adapted and integrated into a coherent system.
- Paper was invented in ancient China as early as the 2nd century AD, though archeological evidence suggests that it was invented much earlier. The technology then spread westward along the Silk Road and was

acquired by the Abbasid caliphate in the 8th century. Papermaking spread across the Muslim world and finally reached Western Europe, through Al-Andalus, around the 12th century.

- When paper was first introduced into Europe, it wasn't widely adopted because it was more fragile and perishable than parchment. Also, because Chinese calligraphy was applied with a brush, paper made according to the Chinese process was too soft and absorbent for use with quill pens. European papermakers addressed this limitation by developing a process for coating the paper with wheat starch or gelatin to harden its surface. This process, called sizing, contributed significantly to the acceptance of paper in Europe.
- Gutenberg tried using sized paper for letterpress printing, but the hardened surface didn't absorb the ink, and the printed characters smudged easily. After much experimentation, he discovered that dampening each sheet would soften the sizing enough to achieve a sharp impression. However, a new problem arose because the only available ink—the water-based concoction used by scribes—proved to be incompatible with this process. When applied to dampened paper, it blurred and bled through to the back of the sheet.
- To address the issue, Gutenberg followed the lead of Renaissance artists, who had developed a process for making oil paints by mixing mineral and vegetable pigments with linseed oil. He used soot (obtained from chimneys) as his pigment and mixed it with linseed oil and turpentine to create a fine black ink that wouldn't blur when applied to dampened paper.

Moveable Type

- Gutenberg's greatest technological challenge was the development of movable type—a printing system in which a unique piece of type is created for each character in a written language. In the printing lexicon, each piece of type is called a sort.
- At a minimum, a set of movable type for the English language required 26 different sorts for the lowercase letters (known formally as miniscule characters), 26 more for the capital letters, 10 for the numbers, and

Moveable type

additional sorts for punctuation marks and blank spaces of various sizes. And given that most characters appear many times on a typical page of text, multiple copies of each sort were needed.

- To prepare a page of text, first, the typesetter would assemble individual sorts into lines of text on a tray, called a composing stick. The line was then transferred into a frame (which Gutenberg called a forme). When the full page of text had been set, the sorts were clamped together with wedges.

For efficiency, early printers developed a standard system for storing their sorts in two sets of bins—one for the miniscules and one for the capitals. Because the miniscule letters were used more frequently, they were stored in the lower, closer set of bins—which is why they're called lowercase letters, even to this day.

- To complete the printing process, the printer would ink the forme, add a paper mask (called a frisket) to ensure that excess ink around the margins of the forme didn't smudge the paper, and then press a sheet of paper onto the inked type to create one impression of one page.

- Like paper, movable type was invented in China; however, it evolved through a series of incremental steps. This process probably began in the 5th century, when the Chinese began using carved wooden blocks to stamp individual symbols or letters onto paper. By the 7th century, these simple stamps had evolved into true wood-block printing. By the late 14th century, the Chinese technique had also spread to Europe, where it was used primarily for printing pictures.

- Between the 11th and 13th centuries, Chinese printers developed workable systems of movable type, using characters made of fired clay or wood; and by the early 15th century, cast-bronze type was being used in Korea. These developments were enormously important and provided uniformity in printed products.

- However, because the Chinese and Korean written languages are logographic—meaning that they use graphical symbols to represent words or ideas rather than sounds, as in an alphabetic system—they used tens of thousands of characters, which made their associated systems of movable type too complicated for routine printing. Despite the uniformity they brought, these pioneering systems did not replace the traditional hand-drawn calligraphy or hand-carved block printing.

Moveable type for Chinese characters

- Scholars believe that the idea of movable type diffused westward from China to Europe, where the use of alphabetic languages greatly increased its potential for practical use. Gutenberg had not only the insight to recognize the economic potential of movable type but also the ingenuity to develop a process for fabricating cast-metal type quickly, cheaply, and precisely. To implement this process, Gutenberg developed an integrated suite of three tools.

- The first tool—called a punch—is a hardened steel bar with the mirror image of an alphabetic character carved into one end. The punch was driven into a bar of soft copper to create an indentation of the alphabetic character. The punched copper block, called a matrix, was then used as part of the only truly original invention in Gutenberg's printing system—the hand mold. This device was composed of two nearly identical L-shaped halves, which were assembled to create a rectangular cavity into which molten metal would be poured to cast the sort.

- To prepare for casting, the matrix was inserted into the bottom of the hand mold. The sort was then cast by pouring molten metal into the cavity. The metal developed by Gutenberg for this purpose was an alloy of lead, tin, and antimony.

Because of his father's work at the Mainz mint, Gutenberg was probably familiar with punches—which had been used since antiquity for striking coins. And Gutenberg's own experience as a goldsmith likely contributed to his formulation of the metal alloy used for casting the sorts.

- A typical page of text used about 3000 characters; thus, hundreds of copies of each character were needed to compose a single page. Using Gutenberg's system, these copies could be made quickly and uniformly. His system was so brilliant that it was used, with only minimal modifications, for nearly 5 centuries after its invention.

Mechanical Printing Press

- The concept of a mechanical press was not a new invention. Screw presses had been used since antiquity for making wine and olive oil and, more recently, for papermaking. But Gutenberg masterfully adapted his press to the unique demands of printing. His machine had five main components:

- a massive wooden frame in which a screw-driven plate—called the platen—was mounted;
- a lever that was used to lower the platen by rotating the screw;
- a sliding bed, on which the forme and its assembled blocks of lead-alloy type were positioned;
- a device called the tympan, which consisted of a piece of cloth stretched across a hinged wooden frame; and
- a hinged frisket, mounted above the tympan.

To prepare the machine for printing, one worker would use two leather pads to ink the forme while another would position a sheet of paper on the tympan. The frisket was then lowered to protect the margins of the paper from being smudged by excess ink, and both the tympan and frisket were rotated onto the inked forme. The sliding bed would be pushed inward to position the forme beneath the platen, which would then be lowered until it pressed the paper firmly onto the inked type to create an impression. Finally, the sequence was reversed, and the printed page was removed from the press.


Gutenberg taking the first proof

Gutenberg's Bible

- Gutenberg's true genius was revealed not just in the details of his press's design but also in his recognition that such as machine was needed at all. He understood that mechanizing the process would reduce variability and human error and thus could deliver substantially higher quality with significantly better consistency. The effectiveness of these features is evident in the consistently stunning quality of the Gutenberg Bibles. Approximately 180 copies of this iconic text were produced; about 40 have survived, and each one is considered a priceless treasure.

- In developing this project, Gutenberg used a high-quality hand-copied Bible as a model for his typeface, page layout, and other aspects of formatting. In replicating the hand-drawn script of the scribal model, he devoted meticulous attention to the most minute details.

One aspect of Gutenberg's typographical invention that has survived is right justification. This feature wasn't possible in a hand-copied text, so Gutenberg probably intended it as a subtle demonstration of his technology's unique capabilities.

- Unfortunately, Gutenberg's obsession with quality also contributed to his downfall. His Bible project took 3 years to complete—even though he had set up a second workshop to expedite the work. Throughout this period, Gutenberg's financial backer, Johann Fust, had received no return on his substantial investment, and by 1455, Fust wanted out. Even though the Bible project was nearing completion, Fust demanded full repayment of his loan, with interest.

- Because Gutenberg had sunk all his money into the business, he couldn't pay Fust—who sued and won, gaining possession of Gutenberg's second workshop and the entire print run of Bibles. Fust then took over the business and went on to achieve great success as a printer in Mainz, while Gutenberg spent the rest of his life struggling to reestablish his own business. Fortunately, even though Gutenberg was deprived of well-earned rewards during his lifetime, the long-term social, political, and economic consequences of his technological triumph have cemented his reputation as one of the most influential people in history.

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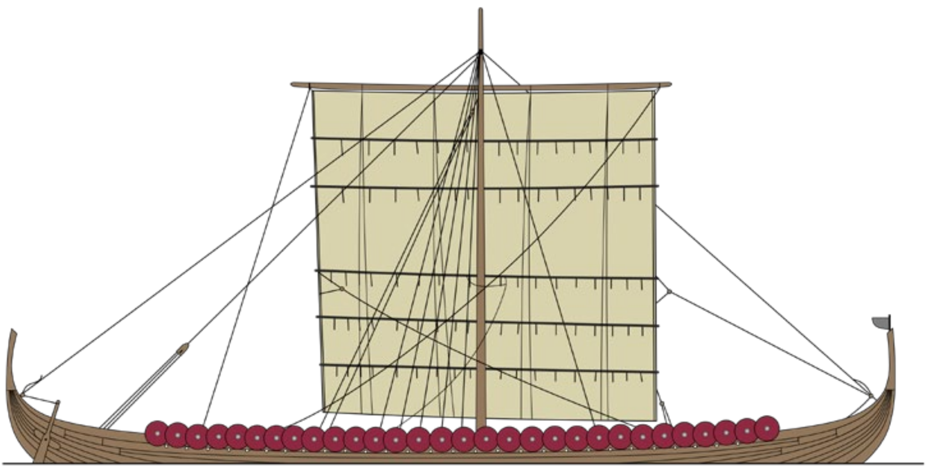
22

Early Mediterranean Shipbuilding: The *Dromon*

A ship is an engineered system composed of four or five closely related technological subsystems: hull structure; hull form; a steering system; a means of propulsion; and, in the case of a warship, armament and protection. During the medieval period, each of these subsystems underwent dramatic advances, and the story of these advances is a fascinating case study in technological change. This lecture focuses on the evolution of the Byzantine warship, the *dromon*, from its Roman ancestor, the *liburna*.

The Roman Liburna

In antiquity, two distinctly different shipbuilding traditions emerged—one in the Mediterranean and one in northern Europe. The northern tradition originated in Bronze Age Scandinavia and achieved its peak in the famous Viking longship. The Mediterranean tradition originated with the Phoenicians and Greeks, then passed through the Romans to the Byzantine Empire, which produced a highly capable war galley called the dromon.



Viking longship

Just as the Byzantine Empire was an outgrowth of the ancient Roman Empire, so the dromon evolved directly from a small Roman galley called the liburna, which was the mainstay of the imperial fleet from the 1st century BC onward. During that era, Rome had gained uncontested control of the Mediterranean, so its fleet needed few of the large warships that had been common during earlier wars against Carthage and Greece.

- The light, nimble liburna was employed primarily as a patrol craft—to protect merchant shipping from pirates and to support land operations. Configurations varied, but the typical liburna was an undecked 50-oared bireme, with rowers seated on two levels.

- The liburna was armed with a bronze ram at the waterline and had an elevated fighting platform for marine infantry and archers at the bow. Like most ancient Mediterranean ships, the liburna was square-rigged—meaning it was equipped with a rectangular sail, which was used primarily for long voyages. In battle, when the reliability and responsiveness of oar power were essential, the mast and sail were usually dismounted.

- After Rome fell, the Byzantines continued to operate liburnae for several centuries; however, in the mid-6th century, references to a new type of ship—the dromon—began appearing in sources. Early versions of this ship incorporated three principal improvements over its Roman predecessor:

    - A slender hull was fully decked and was built using a more robust construction method.

Model reconstructions of Roman ships

- The bronze ram was replaced with a wooden spur, mounted above the waterline.
- In place of the traditional rectangular sail was a triangular—or lateen—sail.

The dromon served as the Byzantine Empire's principal warship for 5 centuries, from the 6th through the 11th century.

Buoyancy and the Liburna Hull Structure

- Hull structure is strongly influenced by a vessel's buoyancy. Archimedes's principle of buoyancy says that a floating object displaces an amount of water that weighs the same as the object itself. Thus, a floating 1-pound boat occupies the same space that was previously occupied by 1 pound of water. This displacement causes an upward force—called the buoyant force—which counterbalances the boat's weight and, thus, keeps it afloat.

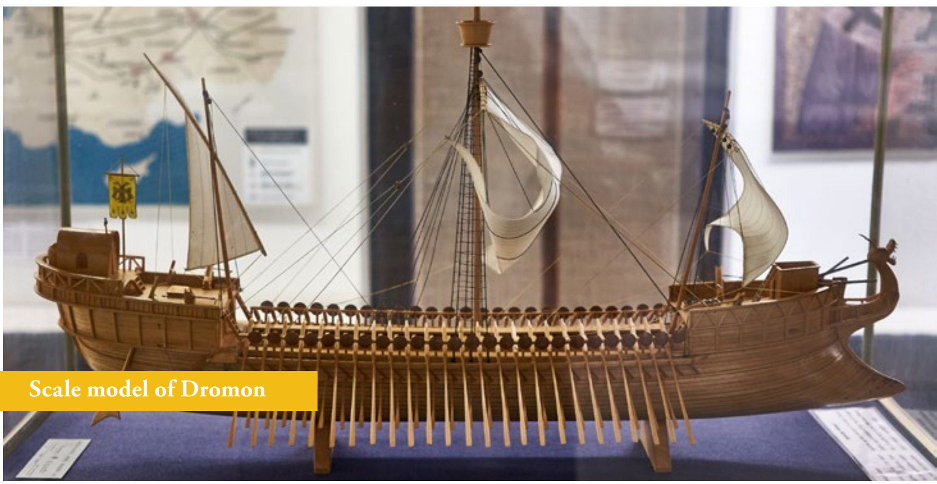
- When a ship is floating on a calm sea, the buoyant force is more or less uniformly distributed along the hull's length. But in high seas, the water's ever-varying surface can cause substantial nonuniformity in the buoyant force. When the ship crosses a large wave, the buoyant force is concentrated amidships—and the hull bends in a mode called hogging. And when the ship is between two waves, the buoyant force is concentrated at both ends, and the hull bends in the opposite mode, called sagging.

- To resist these bending effects, the hull must function as a structure. The keel is an important part of this structure, but it alone doesn't provide enough strength to withstand the extreme loads imparted by rough seas. When the hull sags, its upper edges—called gunwales—flex outward. And when it hogs, the gunwales flex inward. Because this lateral flexibility reduces the hull's overall strength and stiffness, early shipwrights incorporated thick planks—called wales—into the hull structure, and they added crossbeams to tie the wales together. These features ensured that the hull resisted bending as an integrated structural entity.

- With few exceptions, the hulls of ancient ships, such as the liburna, were constructed using a shell-first method, which entailed laying the keel and then assembling the outer planking before any internal framing was added. The planks were joined using closely spaced mortise-and-tenon joints. Holes were drilled through the planks and tenons, and wooden pegs were driven into the holes to lock each joint together. These joints were so tightly fitted that the seams were not caulked—the swelling of the planks in water was enough to create a watertight seal.
- Once the outer shell was complete, small internal frames were added—but they served only to maintain the hull's shape and to provide points of attachment for crossbeams and the rowers' seats.

The Dromon Hull Structure

- Because the the dromon have survived, scholars have examined the recovered wrecks of several Byzantine merchant ships for clues about the extent to which dromons inherited the Roman shell-first hull structure. In the 1960s, renowned underwater archeologist George Bass excavated a 7th-century Byzantine cargo ship at Yassiada—a small island off the coast of Bodrum, Turkey. The ship, which was contemporary with the



Scale model of Dromon

first-generation dromon, has a relatively slender hull—suggesting that, like the dromon, it was built for speed. It's reasonable to assume that the hull structures of these vessels were similar.

- The Yassiada ship was similar to ancient shell-first ships in some respects, but it also differed in important ways. Evidently, by the 7th century, traditional Mediterranean shell-first construction was in transition toward a fundamentally new approach that relied upon internal frames rather than planking as the principal source of the hull's structural strength. Mortise-and-tenon joints were still being used but only to hold the planks in position until they could be nailed to the frames.

- When the Yassiada ship was built, this new paradigm was evidently still a work in progress, but by the 11th century, it would mature into a fundamentally new frame-first approach called carvel construction. Carvel-built hulls were essential features of the later, revolutionary carracks—the robust oceangoing ships of the age of discovery.

Other Features of the Dromon

- During classical antiquity, ramming was the primary tactic used in naval warfare. In battle, galleys like the Greek trireme were employed as human-powered torpedoes, using their heavy bronze rams to disable or sink enemy ships. But by the early Middle Ages, ramming tactics had been rendered obsolete by the new hull structure, because its structural strength lay primarily in robust internal frames rather than in a thin outer shell. Thus, the dromon had no need for a ram, which was replaced with a spur.

- Once the ram became obsolete, naval forces would first engage each other at long range with missile weapons, such as crossbows and catapults. Then, once the opposing ships were close enough to permit boarding, their contingents of marine infantry fought hand to hand across the decks, until one side gained control of the opposing vessel. The dromon's full deck protected the oarsmen from the opening missile attack, and its spur was used to immobilize enemy vessels by shearing off their oars, in preparation for boarding.

- The dromon's other distinguishing feature—its triangular lateen sail—was by no means unique to this vessel. Throughout classical antiquity, rectangular sails had been used almost exclusively; however, between the 5th and 7th centuries, lateen-rigged ships completely replaced square-riggers throughout the Mediterranean.

A notable exception to the usual use of boarding tactics was the Byzantines' occasional employment of an innovative incendiary weapon called Greek fire. Developed in the 7th century, Greek fire was a highly flammable liquid that was sprayed from a device called a siphon, mounted near the bow of a dromon. Once ignited, this liquid burned so intensely that it was nearly impossible to extinguish—and thus was especially effective against combustible wooden ships. The chemical composition of Greek fire is still unknown today.

Mechanics of Sailing

- The simplest of sailing situations is one in which a ship is sailing in the same direction as the wind. In this situation (which mariners call running), the wind is perpendicular to the sail and, thus, exerts its greatest possible pressure on the sail, resulting in a force (F) that propels the ship forward.

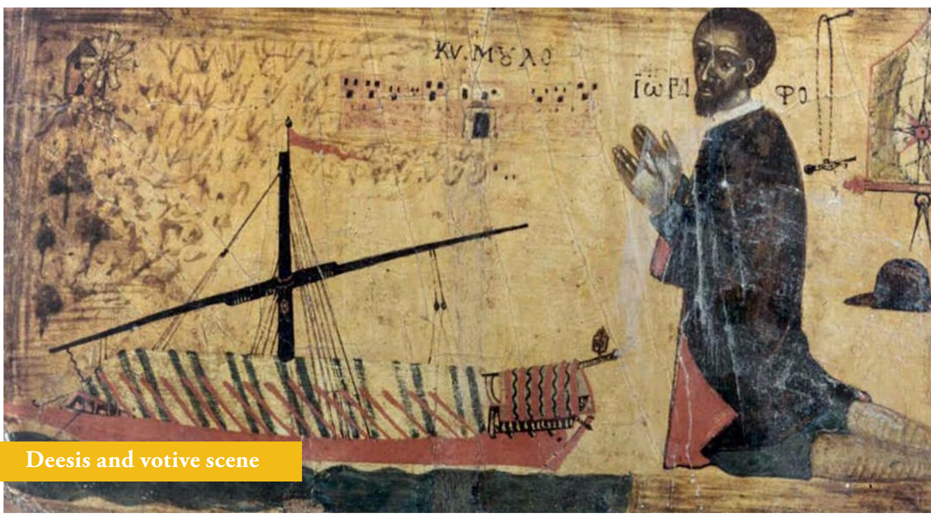
- Now, consider a different wind direction, one which mariners would describe as 2 points abaft the starboard beam. The beam is the direction perpendicular to the ship's keel, and starboard is the right-hand side. The word *abaft* means "in the rearward direction," and a point is one subdivision of the mariner's 32-point compass—a medieval invention. Thus, if the ship were sailing due north, a wind 2 points abaft the starboard beam would be blowing from the east-southeast.

- In this situation, mariners would need to determine the angle at which to set the sail in response to this wind direction. If the sail remained perpendicular to the keel, the wind would have relatively little effect because it would hit the sail at a very shallow angle. Indeed, at that sail angle, the effective propulsion force—that is, the portion of the maximum possible wind force that acts parallel to the keel—would only be about 15% of *F*.

- If the sail was oriented perpendicular to the wind, the full force would be developed, but because of its direction, the sail would push the ship more sideways than forward—a phenomenon called leeway (or leeward drift). Leeway can be problematic because it tends to push the ship off its intended course. To address this issue, mariners would need to find an optimum sail angle that would maximize the propulsion force while also keeping leeway manageably low.

- For centuries, mariners have estimated the optimum sail angle by using a simple rule of thumb: The sail should be set such that the angle between the wind and the sail is equal to the angle between the sail and the ship's keel.

- According to this rule, with the wind blowing from 2 points abaft the beam, the sail should be set with 5 points between the keel and sail and 5 points between the sail and the wind. At that angle, the propulsion force is about 58% of the maximum wind force, and the force contributing to leeway is only 38%.



Deesis and votive scene

Square versus Lateen Rigging

- Although sailing directly into the wind is obviously impossible, in theory, a ship should be able to sail 1 or 2 points off the wind and still make some headway. But in practice, this isn't true. The reason has to do with rigging.

- In general, a square-rigged sailing ship has two types of rigging—standing and running. The standing rigging consists of ropes called shrouds and stays—the sole purpose of which is to support the mast. Standing rigging is seldom, if ever, moved after it's been installed, hence its name.

- The running rigging is used to control the sail and the yard from which the sail is suspended. The principal components of this type of rigging are a halyard, which is used to raise and lower the yard; lifts, which control the yard's angle of tilt; braces, which control the sail angle; and sheets, which control the lower corners of the sail.

- For a ship to sail into the wind, the yard must be rotated as close to the fore-and-aft orientation as possible (more or less parallel to the ship's keel). This configuration is called close-hauled. But the yard's rotation is physically limited by the standing rigging and cannot rotate beyond about 3 points (about 34°) off the keel line. At best, a square-rigged ship can sail only about 6 points off the wind.

- The lateen rig imposes no physical constraint on the sail's orientation. The yard still needs to be angled somewhat to provide propulsion, but a well-designed lateen-rigged ship is fully capable of sailing within 4 points of the wind—2 points better than the square-rigger. This advantage is the primary reason that the lateen rig replaced the square rig throughout the Mediterranean by the 7th century.

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23

Longship, Cog, and Carrack

In June 793, a band of Norse marauders attacked the undefended abbey of Lindisfarne—an island off England's northeastern coast. This raid ushered in the Viking Age, a 3-century period in which these Norwegian, Danish, and Swedish warriors terrorized Europe—sometimes sacking coastal settlements, sometimes sailing up rivers to attack inland cities, and sometimes engaging in peaceful trade. By the end of the 9th century, they were able to conduct large-scale seaborn invasions—leading to the establishment of permanent Viking domains in Britain, Normandy, and beyond. The Vikings' astonishing successes as warriors, traders, and explorers were enabled by their mastery of nautical engineering. This lecture examines Viking vessels and how the northern European shipbuilding tradition evolved over time.

Clinker Construction

- The basic design concept of Viking vessels is quite well-documented, thanks to the Viking tradition of burying deceased chieftains along with their ships. For example, the Gokstad ship was excavated virtually intact from a burial mound in the late 1800s. Built around 890, its large hull was 78 feet long, 17 feet wide, and constructed almost entirely of oak. The Gokstad ship is classified as a *karvi*, which could be used as either a warship or cargo carrier and was fully capable of sailing on the open ocean.

- The Gokstad ship is also a fine example of the northern European shipbuilding tradition. Its characteristic use of overlapping planks to form the hull's outer shell is called clinker construction.

- During construction, a massive T-shaped keel was laid down, and then nine 1-inch-thick strakes were installed to form each side of the hull, up to the waterline. The term *strake* refers to a plank that runs the full length of the ship, from stem to stern.

- Next, a thick wale was added at the waterline, and a crossbeam was installed over each rib and pegged to the wale on both sides. Additional strakes were installed to provide the ship with enough freeboard for sailing in rough seas, and oar ports were cut through one of these strakes on each side.

Gokstad ship

- The upper strakes were strengthened and stiffened by curved elements—called knees—pegged to the planks and crossbeams; by supplemental ribs; and by the gunwales, from which the Vikings hung their shields while underway. The ship's deck was made of pine boards spanning between the crossbeams. Surprisingly, the ship had no seats; the crewmen sat on wooden chests, in which their personal effects were stored.

- For directional control, the Gokstad ship used a side rudder, called a steering oar, mounted near the stern, on the starboard side. The helmsman operated the rudder by turning a tiller.

The *karvi*, a general-purpose vessel, evolved into two specialized variants: a purpose-built, sail-powered cargo ship called the *knarr*, which could carry about 50 tons, and the *langskip*—the true Viking longship—which was used exclusively as a warship and was often crewed by more than 100 oarsmen.

The Cog

- A major advance in the northern shipbuilding tradition was the development of a merchant ship called the cog, which first appeared in the 10th century and gradually replaced the knarr (and similar ships) as the principal cargo carrier in northern waters.

- Like the knarr, the cog was single masted and square-rigged; but the cog's hull was wider and deeper, thus providing significantly more cargo-carrying capacity—80 to 200 tons—and more freeboard for travel in rough seas. Because there were so few well-developed port facilities during this era, early cogs had flat bottoms, so the ships could be landed on undeveloped beaches for loading and unloading.

- The need to facilitate beaching also dictated the cog's unique hull structure, which used traditional clinker-style strakes on the sides but thicker flush-mounted planking and a very shallow keel on the bottom. The early cogs would have performed poorly when sailing into the wind because the flat bottom and shallow keel weren't capable of resisting leeward drift.

- As port facilities improved, the flat-bottomed hull became unnecessary, and later cogs adopted a more rounded hull form and a deeper keel. The seaworthiness of this second-generation cog was further enhanced by a full deck, more freeboard, and something new—a sternpost rudder, which was better suited for the taller hull than the side rudder.

- The cog's tall hull also proved highly effective for defense against pirates because archers assigned to a cog's crew could shoot down on the low-slung galleys that pirates favored. The pirates responded by adding elevated castles to their galleys, but cog builders followed suit, and eventually, the forecastle (or fo'c'sle) and aftercastle became characteristic features of the cog and enhanced its effectiveness as a general-purpose warship.

- Most northern European ships, including the cog and the knarr, continued to use rectangular sails long after Mediterranean ships had switched to the lateen. Even though lateen-rigged ships could sail closer to the wind, square-riggers had two important advantages: They could sail faster when running with the wind, and they could be operated by smaller crews.

Cogs

Shipbuilding Traditions Converge

- As the cog was developing into the most versatile oceangoing ship of its time, Mediterranean shipbuilders were focused on building ever-more-capable galleys—most notably, a large merchant ship called the great galley, which could be propelled either by oars or lateen sails and had a cargo capacity of 150 tons. The great galley was developed by the Venetians and produced at the famed arsenal of Venice—a state-owned shipyard that was the largest industrial complex in Europe until the Industrial Revolution.

- In the late 13th century, Genoese and Venetian merchant galleys ventured out of the Mediterranean for the first time to facilitate the ever-expanding textile trade between Italian republics, Flanders, and England. Initially, northern European square-riggers were unable to reciprocate because the westerly prevailing winds at the Strait of Gibraltar prevented them from exiting the Mediterranean after having entered. However, by 1300, this limitation had been overcome by improvements in sails and rigging—and northern cogs were plying the Mediterranean as both traders and privateers.

- These cogs made a big impression on Italian and Iberian shipbuilders. Cogs were not only more seaworthy than any Mediterranean galley but also cheaper to build, and they could be operated by significantly smaller crews. Within a decade, both the Genoese and Venetians were building large numbers of cogs. But they didn't just copy the northern European design; rather, they applied their unique expertise to overcome the cog's two most fundamental shortcomings.

- First, the northern cog's overall size was constrained by the inherent structural limitations of clinker construction. Larger hulls required multiple layers of overlapping planking—a terribly inefficient configuration, as iron nails needed to pass through each layer of wood to hold them together.

- Italian shipbuilders addressed this limitation by building cogs with carvel hulls. In carvel construction, the ship's framing was built first, as a standalone structural entity, and then the planking was added. The individual planks were flush mounted—not overlapping—and were fastened to the frames but not to each other. The seams between planks were then caulked.

The Genoese built cogs that retained the rectangular sail, capacious hull form, castles, and sternpost rudder of their northern cousins, but the Genoese cogs were three times larger.

- The northern cog's second major limitation was the relatively poor handling that resulted from its use of a single sail. When the wind strikes a sail, it exerts pressure over the sail's entire surface; this pressure can be represented as a discrete force acting at a single, theoretical point—called the center of effort, or CE. The CE is located at the geometric center of the sail.

- Similarly, if the wind pushes a ship sideways through the water, this movement is resisted by water pressure that's applied across the entire submerged surface of the hull. This pressure can also be represented as a force applied at a single, theoretical point—called the center of lateral resistance, or CLR.

- Ideally, the mast of a single-masted ship should be positioned such that the CE is directly above the CLR. This alignment is called the balanced condition. But if the CE is aft of the CLR, then the force of the wind tends to turn the ship into the wind—a phenomenon called weather helm. Conversely, if the CE is forward of the CLR, the wind turns the ship in the leeward direction—called lee helm. If the ship has adequate forward speed, both weather helm and lee helm can be corrected with the rudder, but it also slows the ship.

- The greatest challenge in achieving balance is that the position of the CLR can shift, and when it moves, a balanced ship will become unbalanced. This challenge was addressed around 1350, when Mediterranean shipwrights started fitting cogs with a second mast. Called the mizzenmast, it was positioned near the stern and carried a small lateen sail that could be adjusted to move the overall CE forward or aft. Through this mechanism, the sails could actually be used to steer the ship—and the rudder was needed only to make minor adjustments.

- As cogs got progressively larger, the size of the mainsail had to increase in proportion; but eventually, the sail became too large and unwieldy for the crew to handle. The solution was to add another mast—called the foremast—and use two smaller rectangular sails rather than one big one. Two other sails were added as well, a topsail and a spritsail.

The Carrack

- Having gone through so many modifications, the cog had evolved into a fundamentally new type of full-rigged ship. The Italians called it a *cocca* (revealing its evolution from the cog), the Portuguese called it a *nau* (which simply means "ship"), and the English used the term *carrack*.

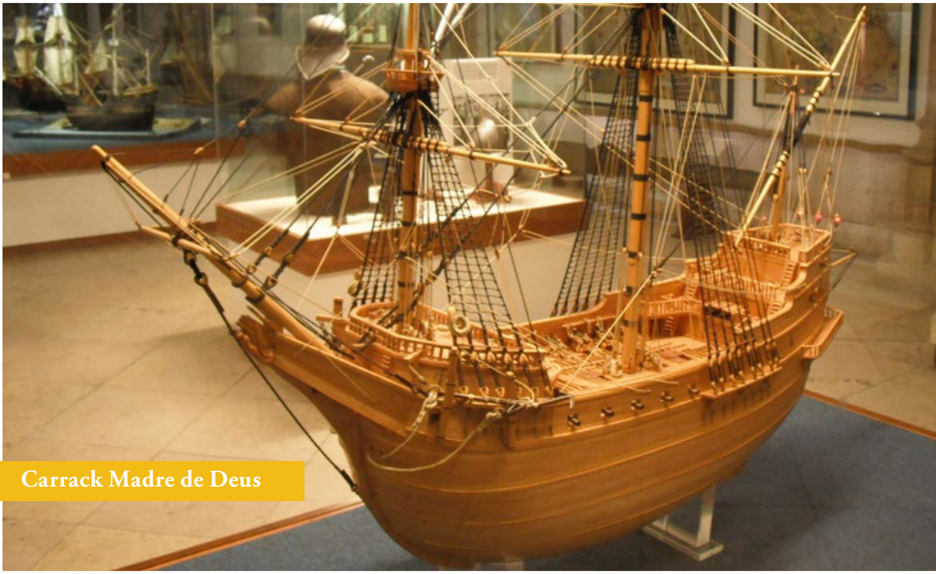
- The carrack was robust, seaworthy, and versatile. The basic design was applied to ships ranging from Columbus's 100-ton *Santa María* to the enormous 1600-ton Portuguese merchant ship *Madre de Deus*. Because of its versatility, the carrack was used extensively in commerce, exploration, and warfare. The width and stability of the carrack also provided an ideal platform for the recently developed gunpowder weapons that were already revolutionizing land warfare.

- The age of discovery began in the early 15th century, as Portuguese navigators began systematically exploring the west coast of Africa in search of an eastward passage to the Indian Ocean. Initially, their preferred ship was the caravel—a small, highly maneuverable lateen-rigged vessel that was well suited for exploring shallow coastal waters in adverse winds. But by the time Bartolomeu Dias rounded the Cape of Good Hope in 1488, it was clear that ships with more cargo-carrying capacity were needed for such long voyages. The carrack met this need and became the key technological enabler of the great voyages of discovery—from the late 15th century until it was superseded by the galleon in the 16th century.

- The renowned naval architect Colin Mudie designed a reconstruction of the ship *Matthew*, which John Cabot sailed from Bristol, England, to North America in 1497. Mudie's ship was created to commemorate the 500th anniversary of Cabot's voyage in 1997. Although the reconstruction is a faithful representation of a late 15th-century full-rigged ship, scholars know very little about the original *Matthew*. However, it embodied all the most important achievements of medieval nautical technology:

- a hull form that optimized seaworthiness and carrying capacity;
- a frame-first ship design that exhibited robust carvel construction;
- a sternpost rudder;
- a combination of rectangular and lateen sails that provided effective propulsion, balanced handling, and enhanced steering; and
- an integrated system of standing and running rigging that provided structural support and flexible control.

The most astonishing characteristic of this ship is that it crossed the stormy North Atlantic in 34 days and then returned home safely with a crew of just 18 men. It's a stunning testimonial to the efficiency of this superbly designed mechanical system—and to the ingenuity of the medieval shipwrights who crafted it.



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24

The Modern Legacy of Medieval Technology

This course has examined products of medieval engineering in four major thematic categories: enabling technologies; military technologies; works of civil, structural, and construction engineering; and mechanical systems. This lecture explores one more important invention—eyeglasses—which doesn't fit neatly into any of those four categories but does exemplify the legacy of medieval technology, in that it's a common feature of modern life that most people don't associate with the Middle Ages, and it was not developed as an application of any scientific principle or theory. This lecture also revisits three technological innovations that demonstrate a shift in the medieval design process from an empirical approach toward a more conceptual—and more modern—approach to design. It concludes with a look at how medieval technology continues to impact modern daily life and how it has advanced the human condition more broadly.

The Invention of Eyeglasses

- Archeological evidence suggests that rock crystals were used as magnifying lenses as early as the 7th century BC. And Pliny the Elder, the 1st-century Roman natural philosopher, observed that a glass globe filled with water would magnify objects placed behind it. Scholars also suspect that the 2nd-century mathematician Claudius Ptolemy discussed convex lenses in his treatise on optics—though this can't be confirmed, because the only surviving copy of this work is incomplete.

- During the High Middle Ages, the first man-made magnifying glasses—called reading stones—were produced by cutting glass spheres in half. And once this simple invention proved its usefulness, it was only a matter of time before some enterprising artisan mounted two reading stones in a frame and perched it on his nose. This event probably occurred around 1290 in Italy, but sources don't provide a definitive confirmation until 1306, when a Dominican theologian named Giordano da Pisa wrote, "It is not yet twenty years since there was found the art of making eyeglasses, which make for good vision."

- The medieval artisans who developed the first eyeglasses had no scientific understanding of optics or human physiology. It wasn't until the early 17th century that Johannes Kepler published the first scientifically valid explanation for how lenses correct faulty vision.

- Today, scientists know that the physical phenomenon that makes eyeglasses work is refraction—the tendency of light rays to bend when they pass from one medium into another. Because of this phenomenon, a convex lens causes parallel light rays to focus at a single point behind the lens, while a concave lens causes these rays to diverge.

- This phenomenon is also essential for human vision. The cornea and lens at the front of an eye refract the incoming light toward a focal point on the retina—the eye's light-sensitive inner layer of tissue. There, the light is converted into electrical impulses that are transmitted through the optic nerve to the brain, where they're processed as visual images.

Human vision is sometimes impaired by refractive error, which occurs when the shape of the eye causes the focal point to fall in front of the retina (nearsightedness) or behind the retina (farsightedness). And because the science is understood today, vision specialists know that eyeglasses correct refractive error by shifting the focal point onto the retina. A concave lens moves the focal point farther away, while a convex lens moves the focal point closer.

Ugo da San Caro

A Gradual Shift in Approach to Design

Engineering in the Middle Ages was based on experience, judgement, incremental adaptation, and sometimes accident—but virtually never on science. The modern conception of engineering as an application of science simply doesn't apply to the Middle Ages. The earliest scientific principles that would eventually be applied to engineering didn't appear until the 17th century, and they weren't widely adopted by practicing engineers until the 19th century.

- Nonetheless, the late Middle Ages saw a few subtle hints of what the future would bring, including three innovations discussed in previous lectures. The first is Filippo Brunelleschi's design for the great dome over the Cathedral of Santa Maria del Fiore in Florence, Italy. The scale and configuration of this dome were so unprecedented that it couldn't be designed by making incremental changes to previously successful designs—as had been done for other great structures, such as the Gothic cathedrals.

- Brunelleschi had to meet the project's unique demands by drawing upon abstract structural ideas—such as configuring masonry bedding surfaces in a way that would cause the octagonal dome to carry load as if it were hemispherical. This conceptual approach was a significant step toward a more modern approach to design.

- A second example of this shift in approach is the astronomical clock—an elaborate mechanical system that predicted and displayed the positions of the sun, moon, and planets. While the underlying medieval understanding of planetary motion was scientifically incorrect, the process of translating an overarching astronomical scheme into mechanical gearsets and linkages required a conceptual design that was significantly beyond the medieval norm.

The ancient Greeks had made a similar conceptual leap as the late medieval engineers who designed the astronomical clock. The famous Antikythera mechanism is an astonishingly sophisticated Hellenistic-era astronomical computer that was recovered from a shipwreck in 1901. But because this unique machine was lost and forgotten for 2000 years, it had no known influence on subsequent technological development. Thus, the medieval astronomical clock was an original invention of the Middle Ages.

- A third example is the medieval transition in shipbuilding from shell-first to frame-first construction. Nautical archaeologists have demonstrated that the shell-first ship generally wasn't built according to a predetermined plan; rather, the shipwright developed the hull form as it was being built—by adjusting each individual plank as it was added.

Reconstruction of a Viking ship

- With the advent of frame-first construction, the shapes of the frames had to be worked out in advance so that the resulting hull form was smooth, well-proportioned, and seaworthy. This process required a fundamentally new design approach—one that began with a predetermined hull form, from which the shapes of the individual frames could be extracted. This new approach took a long time to develop fully.

- None of these examples involve the application of science to engineering design, but they do involve the application of abstract geometric concepts. This was a small but important step toward science-based design and an equally important step away from the purely empirical approach that had characterized nearly all the engineering of earlier eras.

The nascent conceptual approach to design is one of the most consequential legacies of medieval technology.

Sites to Visit

- The most tangible legacies of medieval engineering are the many technological artifacts—cathedrals, castles, monasteries, bridges, mills, clocks, weapons, ships, and more—that have been preserved in towns and cities all over Europe and in museums around the world. Visiting places such as Carrickfergus Castle, Rievaulx Abbey, or Amiens Cathedral is a great way to engage with such artifacts more directly. And many similar examples can be found throughout Europe.

Fountains Abbey

- The Royal Armouries Museum in Leeds, England, has one of the world's finest collections of medieval and postmedieval arms and armor. At the Gutenberg Museum in Mainz, Germany, visitors can see a reconstruction of Gutenberg's workshop and two original Gutenberg Bibles. Also in Germany, the town of Rothenburg ob der Tauber is renowned for the superb state of preservation of its medieval core. Here, one can see fine examples of traditional timber construction and a complete circuit of medieval walls.

- In the *Mary Rose* Ship Hall and Museum in Portsmouth, England, visitors can see the recovered wreck of the huge carrack—Henry VIII's flagship, which sank in 1545. Equally impressive are the recovered artifacts, which include cannons, longbows, pulley blocks, ropes, tools, utensils, a magnetic compass, and much more.

- To see the contrast between medieval-style fortifications and the low, angular *trace italienne* system that was developed in response to gunpowder artillery, there's no better place than Dubrovnik, Croatia, where the two technologies stand side by side.

- A few sites also offer opportunities to experience medieval technological processes. For example, near Treigny, France, a faithful reproduction of a 13th-century castle is being constructed entirely with authentic medieval tools, equipment, and techniques. And at Campus Galli, in Meßkirch, Germany, the 9th-century Plan of St. Gall—the only architectural drawing that has survived from the early Middle Ages—is being used as the basis for reconstructing a Carolingian-era Benedictine abbey.

Medieval Technologies in the Modern World

- Many medieval technologies are still part of everyday life today. For example, when people read books, they're using at least two medieval technologies—paper and printing—and those who read with glasses are using a third.

- People who sell a piece of real estate will likely communicate the size of the plot in acres—a unit of measurement that was defined by the production rate of a medieval ox-drawn plow. Similarly, the furlong—another measurement derived from medieval agriculture—is still used in horse racing.

- These days, most mechanical clocks have been replaced by electrical and electronic devices, but the modern conception of time resulted from the invention of the mechanical clock in the 14th century. From that moment to the present day, people's lives have been regulated by the passage of 24 equal-length hours each day, without regard to the rising and setting of the sun.

- Today, much of the electrical power is generated by turbines that extract energy from moving water and wind in essentially the same way that medieval waterwheels and windmills did.

Wind turbines

- In towns and cities all over the world, updated versions of medieval architectural styles have been applied to innumerable churches, synagogues, mosques, public buildings, college campuses, and private residences. Most of these buildings were products of the Romanesque Revival and Gothic Revival movements, which began in mid-18th century England and then spread across the Western world. Representative American examples are the Neo-Romanesque Trinity Church in Boston and the Neo-Gothic Cathedral of St. John the Divine in New York City.

- Another medieval technology that remains is perspective drawing—a technique for representing a three-dimensional scene on a two-dimensional surface in a way that accurately depicts spatial depth. The formal process of perspective drawing is generally attributed to Filippo Brunelleschi, based on a series of drawings he did between 1415 and 1420. The technique was immediately embraced by Renaissance artists, and even today, it's an essential tool for the creation of representational art, architectural renderings, and engineering drawings.

The perceived size of an object decreases in direct proportion to its distance away from the viewer. In other words, distant objects appear smaller. This linear relationship between size and distance is illustrated by the two most important characteristics of perspective drawing.

- Receding parallel lines appear to converge at a single point—called the vanishing point.
- Equally spaced objects appear to get closer together at progressively greater distances from the viewer.

Advancement of the Human Condition

- Beyond the impacts on everyday life today, medieval technology has also advanced the human condition more broadly. During the Middle Ages, technological developments helped drive world-changing transitions, including shifts from slave labor to greater reliance on free landholders, from human and animal power to greater reliance on water and wind, from handwritten manuscripts to printed books, and from commerce focused largely on supplying luxury goods for the elite to the production of consumer goods for mass markets.

- Inventions like the printing press and the convex lens paved the way for the Scientific Revolution, and the work of Renaissance artist-engineers like Filippo Brunelleschi and Mariano Taccola paved the way for the modern partnership between science and technology. Improved ships and navigational devices opened distant lands to exploration, colonization, and economic development. And a nascent trend toward industrialization—particularly in textiles, ironmaking, and shipbuilding—set the stage for the Industrial Revolution.

- To be sure, some aspects of medieval technological development were harmful or counterproductive. The invention of ever-more-destructive weapons, the spread of diseases to the New World, the exploitation of native populations, and the deforestation of Western Europe are just a few examples of the dark side of the medieval legacy.

- Medieval technologies were also instrumental to a phenomenon that historians call the Europeanization of the world. That can be seen as a good or bad thing—but it's undeniably an important sociological phenomenon that continues to affect lives today. Ironically, this Europeanization of the world was achieved largely with technologies that Europeans borrowed from other cultures; yet, this willingness to borrow—and then to improve upon borrowed ideas—was integral to Europe's success.

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Glossary

abbey: A large, autonomous monastic facility headed by an abbot.

abutment: A foundation element that supports one end of a bridge.

alloy: A metallic substance formed by mixing a pure metal with one or more other elements.

ambulatory: In church architecture, a semicircular aisle that surrounds the apse.

annealing: The process of relieving internal stresses in a metal by heating it to a moderate temperature, then allowing it to cool slowly to room temperature.

apse: A semicircular or polygonal extension to the floor plan of a building.

aqueduct: A human-made structure that carries water from a distant source to a city or town.

arcade: A series of two or more adjacent arches. Also, the lowest level of a cathedral.

arch: A structural element that is used to span across a horizontal distance while carrying load primarily in compression.

ard: A scratch plow used in the ancient Mediterranean world.

arrow loop: In a fortification wall, a narrow slit through which arrows can be launched.

ballista: A Roman stone-throwing torsion catapult with two torsion springs and two throwing arms.

barbican: A fortified gateway that is usually positioned outside the main defensive wall of a castle or fortified city.

barrel vault: A vault with the shape of a half cylinder.

bascinet: An open-faced, closely fitted helmet, often worn underneath a great helm.

basilica: A Roman public building characterized by a large covered central hall. The Roman basilica served as a model for many early Christian churches, which were also called basilicas.

batten: A lightweight wooden beam that directly supports a row of roof tiles.

bay: A square or rectangular module of a building floor plan.

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

beater: In weaving, a pivoting comblike frame used to control the spacing of the warp threads and to push each new pick into position in the woven cloth.

bed stone: The lower fixed stone in a pair of millstones.

belfry: A mobile siege tower.

bellows: An apparatus used to force a stream of air into a furnace or forge.

belt drive: A flexible belt or cord used to transfer rotational motion from one wheel or shaft to another.

bent entrance: A narrow, sharply angled corridor used to enhance the defense of a gateway.

bireme: A rowed warship with oars on two levels.

blast furnace: A furnace used for smelting iron ore to produce cast iron.

block and tackle: A system of ropes and pulleys that provides mechanical advantage for lifting.

blockade: A form of siege warfare in which the besieging force surrounds a castle or fortified town, seals it off from resupply, and then starves its population into submission.

bloom: A solid, spongy, white-hot mass of iron and impurities, created during the smelting of iron in a bloomery.

bloomery: A primitive type of furnace used to smelt iron ore to produce wrought iron.

boat mill: A mill consisting of one or more waterwheels mounted on pontoons and used to extract mechanical power from a river.

bobbin: A component of a flyer spindle. Spun thread is wound onto the bobbin by the flyer spindle.

body-centered cubic: One possible configuration of the crystal lattice of iron.

bolt: A heavy arrowlike projectile launched by a crossbow or catapult (also called a quarrel).

bombard: A large-caliber siege cannon of the late 14th and 15th centuries.

bonnet: On a sailing ship, the removable lower portion of a sail.

bowline: On a square-rigged sailing ship, an element of the running rigging that is used to facilitate sailing into the wind by keeping the forward edge of the sail tight.

bowsprit: A spar that projects forward from the bow of a sailing ship.

brace: On a square-rigged sailing ship, an element of the running rigging that is used to rotate a yard horizontally.

bracket: A structural element used to reinforce the connection between two perpendicular members (e.g., a column and a beam).

brake wheel: In a windmill, the large gear that transmits mechanical power from the windshaft through the wallower to the machinery within the mill.

bridge mill: A floating mill positioned within (or just downstream from) the opening between two bridge piers to take advantage of the faster current caused by the constricted flow.

brittleness: The lack of ductility in a material.

bronze: An alloy of copper and tin.

buckling: A stability failure of a structural element subjected to compression.

buoyancy: An upward force caused by the displacement of water by a floating object.

buttress: A pier or thickened section of a wall that resists the outward thrust of an arch, vault, or dome.

buttress vault: A barrel vault used to restrain the lateral thrust of an arch, vault, or dome.

cam: A post or lobe mounted on a rotating shaft such that the cam moves another mechanical component as the shaft rotates.

cambered vault: A vault that is curved in both the transverse and longitudinal directions.

camshaft: A mechanism that converts rotary motion into reciprocal (or back-and-forth) motion by the action of one or more cams mounted on a rotating shaft.

cantle: The upward-curving rear portion of a saddle.

capital: The decorative top of a column.

capstan: A device for harnessing and amplifying human or animal power to pull a rope. A capstan has a vertical shaft, while a windlass typically has a horizontal shaft.

carburization: A heat-treating process used to transform iron into steel by dissolving carbon atoms into the crystal lattice of the metal.

carrack: An oceangoing carvel-built square-rigged ship with a broad, capacious hull and three or more masts.

carruca: A heavy plow used extensively in northern Europe during the Middle Ages.

carvel construction: A shipbuilding technique in which the keel and frames of a hull are assembled first, then the planking is added. The flush-mounted planks are fastened to the frames but not to each other, so they must be caulked to achieve watertightness.

cast iron: An alloy of iron and 2% or more carbon by weight.

casting: The process of forming a metal into a desired shape by heating it to the melting point and then pouring the molten material into a mold.

castle: The private fortified residence of a lord.

center of effort (CE): The theoretical point at which the force applied to a sail can be assumed to act.

center of lateral resistance (CLR): The theoretical point at which the lateral resisting force applied by water to the side of a ship's hull can be assumed to act.

centering: A temporary structure used to support an arch or vault during construction.

chancel: In church architecture, the apse, ambulatory, and associated chapels, normally located at the east end of the building.

charcoal: A fuel produced by heating hardwood in a reduced-oxygen environment to drive off water and resins. Because charcoal is nearly pure carbon, it is capable of burning at much higher temperatures than wood.

chausses: Protective leggings made of iron mail.

circumferential tension: The tendency of a dome to expand outward under load.

clapper bridge: A primitive bridge consisting of a stone slab spanning between two abutments or piers.

classical antiquity: The historical era encompassing the civilizations of ancient Greece and Rome from the 8th century BC to the 5th century AD.

clepsydra: An ancient Greek water clock.

clerestory: The uppermost level of a Gothic cathedral (and of some Romanesque cathedrals). The clerestory usually incorporates large windows that admit natural light to illuminate the nave.

clinker construction: A shipbuilding technique in which the outer shell of a hull is assembled first, using overlapping planks that are fastened to each other. Internal frames are then added to strengthen the hull.

close-hauled: The configuration of sails and rigging of a ship when sailing into the wind.

coat of plates: An early form of plate armor consisting of an array of steel plates riveted to the inside of a leather or cloth garment.

cobblestone: A pavement created by setting small, rounded stones (cobbles) into a bed of mortar on top of a base layer of compacted sand.

cofferdam: A temporary structure used to construct a bridge pier within a body of water.

cog: A square-rigged cargo-carrying sailing ship with a single mast.

cogwheel: A gear with teeth oriented perpendicular to the plane of the gear.

coif: A protective hood made of leather or iron mail.

collar: A secondary horizontal element in a timber roof truss.

colonnette: A cylindrical element of a compound column.

column: A vertically oriented structural element that is used to support a load above ground level and carries this load primarily in compression.

combustion: A chemical reaction in which a fuel combines with oxygen to produce combustion products and energy.

composite bow: A bow constructed from three different materials—animal sinew, bone or horn, and a wooden core.

compound gearset: A system of gears in which one or more shafts have both a driving gear and a driven gear mounted on the same shaft.

compound pier: A column that is composed of multiple parallel elements.

compression: An internal force or stress that causes a structural element to shorten.

concentric castle: A fortification consisting of two or more concentric curtain walls, each forming a complete, independent circuit, with the inner wall built significantly higher than the outer one.

conduit house: A masonry tank used to collect and control the flow of water at the source of a water supply system.

corned powder: A type of gunpowder that was manufactured by adding liquid to the dry ingredients (charcoal, sulfur, and saltpeter) to create a paste that was then dried to form hard pellets. Corned powder was safer, more consistent, and more powerful than granular gunpowder.

cornice: A decorative architectural element that projects outward from the face of a wall.

coulter: An iron blade mounted ahead of the plowshare on a medieval carruca (heavy plow). The coulter sliced vertically through the sod as the plow moved forward.

counterbalance treadle loom: A technologically advanced type of loom that replaced the vertical warp-weighted loom during the Middle Ages.

counterweight trebuchet: A large medieval siege catapult powered by a heavy counterweight suspended from the short end of the throwing arm.

course: In masonry construction, a horizontal row of stones or bricks.

cranequin: A geared mechanical device used to assist in spanning a crossbow.

crank: A device that uses a handle, offset from a rotating shaft, to produce rotary motion by alternately pulling and pushing the handle.

crank and pushrod: A device that converts rotary motion to reciprocal (back-and-forth) motion and vice versa.

crenellation: A protective battlement consisting of alternating raised segments (merlons) and lower segments (crenels).

cross-plowing: The process of plowing a field twice, in perpendicular directions, to fully pulverize the soil.

cross section: The geometric shape formed by passing a plane through a three-dimensional object.

crossing: In the floor plan of a cruciform building, the square bay at which the two transepts intersect with the nave.

crystal lattice: The geometrically regular arrangement of atoms in a metal.

curtain wall: The outer wall of a castle or fortified city.

cutwater: The pointed end of a bridge pier, intended to guide the flow of the river around the pier.

decarburization: A metallurgical process in which the carbon content of cast iron is reduced by reacting the carbon with oxygen.

decentering: The process of removing the centering from beneath an arch or vault after the arch or vault has become self-supporting.

dendritic drainage: A treelike drainage pattern in which many small tributaries flow into progressively larger streams, which feed into a single main channel and then out into a sea or ocean.

dislocation: In metallurgy, a geometric imperfection or flaw in a crystal lattice.

distaff: A tool used to hold raw fibers while they are being spun into thread.

distribution tank: In a water distribution system, a reservoir that receives water from the main and transmits the water under pressure to multiple distribution pipes.

dome: A hemispherical shell that is used to enclose space.

dorsal-yoke harness: An ancient Roman harness used to hitch a cart, wagon, or plow to a horse.

drafting: The process of controlling the quantity of wool fiber being spun into thread.

draw length: The maximum distance that a bow can be drawn.

draw weight: The maximum pulling force that can be applied to a bow.

drawbridge: A movable bridge crossing a ditch or moat at the gateway of a castle or fortification. A drawbridge is raised to prevent entry into the gateway.

drawplate: A tool used to fabricate fine iron wire by heating a larger-diameter rod or wire and then pulling it through successively smaller holes in the plate.

***dromon*:** A Byzantine rowed warship that was adapted from the ancient Roman *liburna*.

drop spindle: A tool used for spinning raw fibers into thread by hand.

drum: A cylindrical or polygonal wall that supports a dome.

ductility: The capacity of a material to undergo large plastic deformations when loaded.

early Middle Ages: The historical period from approximately 500 to 1000.

early modern period: The historical era from approximately 1500 to 1800.

elastic energy: Energy stored in a deformed material—e.g., a bent bow.

embrasure: In a castle or fortification, an opening through which weapons can be fired.

empirical design: The process of designing a structure, machine, or system by making a succession of incremental changes based on experience and the observed performance of previous designs.

engaged column: A decorative half column projecting from a wall or pier.

engineering: The process of devising a structure, device, machine, or system that meets a human need. The product of engineering is technology.

escalade: In siege warfare, the practice of attacking over an enemy wall.

escapement: A mechanism that subdivides the fall of a weight into discrete segments of equal duration.

face-centered cubic: One possible configuration of the crystal lattice of iron.

feudalism: A characteristically medieval system in which higher-level aristocrats provide land grants (fiefs) to lower-level aristocrats in exchange for military service and an oath of loyalty.

fief: In feudalism, a parcel of land granted to a vassal by a higher-level aristocrat in exchange for military service and an oath of loyalty.

finery: A furnace used to convert cast iron into wrought iron by using a blast of air to reduce the carbon content of the metal.

floor: A wooden element forming the bottom of the frame of a ship's hull.

flyer: In a flying buttress, a half arch that connects the buttress to the supported structure.

flyer spindle: A component of a spinning wheel that twists fiber into thread and winds the thread onto the spindle simultaneously.

flying buttress: A structural element that resists the outward thrust of arches and vaults and is external to the structure it supports.

flywheel: A heavy, rotating disk or wheel mounted on a shaft. Once a flywheel is set in motion, it rotates at a steady rate because of its mass and momentum.

focal point: The point at which refracted light rays are concentrated after passing through a convex lens.

force: A push or pull applied to an object.

force-draw curve: A graph of the force required to draw a bow versus the distance drawn.

forge welding: The process of fusing two or more pieces of metal together by heating them and then hammering them together.

forme: In Gutenberg's printing system, a frame in which pieces of movable type were clamped to print a page.

fracture: The brittle failure of a material.

frisket: In Gutenberg's printing system, a mask used to hold the printed page in position and protect it from smudging.

fuller: The longitudinal groove in a sword blade.

fulling: A process by which woven wool cloth is cleaned, strengthened, and thickened.

fulling stock: A mechanical trip-hammer used for fulling cloth.

furlong: A medieval unit of measurement equal to 660 feet and traditionally defined as the distance an ox could plow before it had to be rested.

futtock: A wooden element forming the side of the frame of a ship's hull.

gaffle: A mechanical device used to assist in spanning a crossbow.

garros: A large arrow fired by an early gunpowder weapon.

gearset: A system of two or more meshed gears, each fixed to its own rotating shaft.

gradient: The slope of a road or water channel.

great galley: A large merchant ship, developed by the Republic of Venice and propelled either by oars or lateen sails.

great helm: A heavy, barrel-shaped helmet used during the High Middle Ages.

Greek fire: An incendiary weapon developed by the Byzantine Empire for use on warships. The system consisted of a highly flammable liquid that was sprayed from a device called a siphon, mounted near the bow of a ship.

groin: The intersection of two adjacent compartments of a groin vault.

groin vault: A vault formed by the intersection of two perpendicular barrel vaults.

gunpowder: An explosive substance composed of sulfur, charcoal, and saltpeter.

gunwale: The heavy wooden rail at the top edge of a ship's hull.

halberd: A Swiss pole weapon that incorporated a spiked tip, an ax blade, and a side spike.

halyard: On a sailing ship, an element of the running rigging that is used to raise, lower, and support a yard.

hanger: A vertical structural element from which a load is suspended. A hanger carries load in tension.

hauberk: A protective tunic composed entirely of iron mail.

head: In fluid mechanics, an elevation difference that drives fluid flow. Head is a measure of potential energy.

headrace: An artificial channel that delivers water to a waterwheel.

heavy plow: See **carruca**.

heddle: A connector made of thread or wire and used to reposition a warp thread during the weaving process.

hematite: A type of iron ore.

High Middle Ages: The historical period from approximately 1000 to 1300.

hoarding: A temporary wooden structure used to augment the stone battlement of a castle or city wall.

hogging: The bending of a ship's hull caused by a large wave amidships. A hogging hull bends concave downward.

hopper: A cone-shaped opening through which raw grain is introduced into a set of millstones.

horizontal waterwheel: A waterwheel that is mounted on a vertical shaft and is driven by water striking the wheel's angled vanes at high velocity.

horse collar: A padded collar used to hitch a cart, wagon, or plow to a horse.

horsepower: A unit of mechanical power equal to 550 foot-pounds per second.

hounskull bascinet: A type of helmet developed for men-at-arms in the late 14th century.

impost: A stone block that supports the base of an arch.

infrastructure: A large-scale technological system that enhances societal functions, facilitates economic development, and enhances quality of life.

karvi**:** A general-purpose Viking ship propelled either by oars or by a single rectangular sail and used as both a cargo carrier and a warship.

keel: The structural backbone of a ship.

keep: A heavily fortified tower at the core of a castle. A keep typically incorporated a cellar, public meeting spaces, a private residence for the lord, and one or more watchtowers.

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

king post: The central vertical element of a tie beam truss.

knarr**:** A Viking ship propelled primarily by sail and used for carrying cargo.

knight: Prior to the 12th century, a member of the nobility who provided military service to a lord in fulfillment of a feudal obligation. In the 12th century, knighthood became a social rank.

lames: Articulating joints in plate armor.

lance: A weapon consisting of a long wooden shaft with a socketed iron head.

langskip**:** A Viking longship propelled primarily by oars and used exclusively as a warship.

lantern pinion: A gear consisting of wooden or metal rods (which serve as teeth) sandwiched between two disks.

late Middle Ages: The historical period from approximately 1300 to 1500.

lateen: A triangular sail.

lath: The bow of a crossbow.

latifundium: A large agricultural estate of the late Roman Empire.

lee helm: The tendency of a ship sailing across the wind to turn in the downwind (or leeward) direction.

leeway: The tendency of a sailing shift to drift in the downwind (or leeward) direction anytime the sail force is not aligned with the keel.

letterpress printing: The process of printing with movable type.

lever: A simple machine that magnifies an applied force through rotation about a fixed axis (the fulcrum).

***liburna*:** A 50-oared Roman galley.

lift: On a sailing ship, an element of the running rigging that is used to support the ends of a yard and tilt it vertically.

ligature: In letterpress printing, a single sort that incorporates two or more characters.

lime mortar: A mixture of lime, sand, and water. The lime is manufactured by baking limestone in a kiln.

load: A force applied to a structure, structural element, or material.

longship: A vessel with a long, narrow hull, propelled primarily by rowers and usually used as a warship.

loom: In weaving, a frame that holds the warp threads in tension while the weft thread is interwoven through the warp.

machicolation: In a fortification, an overhead structure that projects forward from a defensive wall or tower and incorporates a hole in the floor, through which projectiles can be dropped on an attacking enemy.

machine: An assembly of fixed or moving parts used to perform work.

magnetite: A type of iron ore.

man-at-arms: A heavily armored warrior who fought primarily from horseback.

mangonel: A catapult powered by human operators pulling on ropes attached to the short end of the throwing arm. Also called a traction trebuchet.

manor: A medieval agricultural estate managed by an aristocrat (called the lord of the manor) and worked by tenant farmers.

matchlock: A mechanism that enhanced the effectiveness of early firearms by allowing a gunner to fire the weapon by pulling a trigger.

matrix: In Gutenberg's printing system, a copper block with a punched alphabetic character, used for casting movable type.

mechanical advantage: The amplification of an applied force by a mechanical device.

mechanical efficiency: A measure of the efficiency of a mechanical device, calculated as the output divided by the input and expressed as a percentage.

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

medieval: Of or characterized by the Middle Ages.

medieval warm period: A period of climatic change that lasted from around 950 until 1300 and caused longer growing seasons and milder winters throughout northern Europe.

metallic bonding: A type of interatomic bond in which electrons become delocalized from their atomic nuclei and can move freely throughout the crystal lattice of a metal.

Middle Ages: The period of time between classical antiquity and the early modern period. For the purpose of this course, the Middle Ages are considered to extend from 500 to 1500. Also called the medieval era.

millpond: An artificial reservoir, used to control the flow of water to a waterwheel.

mizzen: A small mast mounted near the stern of a sailing ship.

moldboard: A curved wooden component mounted on the right-hand side of a medieval carruca (heavy plow). The moldboard turned the plowed soil and deposited it on the right side of the plow.

mortar: A substance used to fill the gaps between stones or bricks in masonry construction.

mortise-and-tenon joint: A timber connection in which a projecting element (the tenon) of one member is inserted into a matching hole (the mortise) in another element. This joint is sometimes secured with one or more pegs, which are driven into holes drilled through both elements.

motte-and-bailey castle: A fortification consisting of two main components: the motte, a conical mound surmounted by a keep; and the bailey, a larger ground-level enclosure surrounded by a ditch, an earthen rampart, and a wooden palisade.

movable type: A printing technology in which a unique piece of type is created for each character in a written language.

mural tower: A fortified tower that is integrated with the curtain wall of a castle or fortified city.

murder hole: In a medieval fortification, an overhead opening through which projectiles could be dropped on an attacking enemy.

narthex: A porch or enclosed entrance hall of a church.

nasal helmet: A conical helmet with a noseguard, used extensively during the early Middle Ages.

nave: The central hall of a church.

Normans: The descendants of Norse Vikings who settled in the Normandy region of France in the 9th and 10th centuries.

oculus: A circular opening at the top of a dome.

onager: A late Roman and Byzantine torsion catapult with one torsion spring and one throwing arm.

open-channel flow: In fluid mechanics, a type of flow in which the surface of the fluid is at atmospheric pressure. To maintain open-channel flow, the channel or pipe must have a continuous downhill gradient.

overshot waterwheel: A waterwheel that is mounted on a horizontal shaft and driven by water flowing into buckets at the top of the wheel.

ox goad: A long pole used by a plowman to control a team of oxen.

oxidant: A substance that supplies oxygen to enable a chemical reaction.

palintone: An ancient Greek stone-throwing torsion catapult (also called a ballista by the Romans).

palisade: A defensive wall consisting of closely spaced tree trunks or wooden stakes set vertically into the ground.

panemone: A horizontal windmill invented in Persia during the 8th or 9th century.

parchment: A writing material made from the treated skin of sheep or goats.

passing brace: In a timber roof structure, a diagonal element that is parallel to a rafter and shares load with it.

pattern welding: A sword-making technique in which two or more metals of different composition are forge-welded together, then twisted to create an intricate pattern on the finished blade.

pavis: A portable shield used by medieval crossbowmen to provide protection while reloading.

pendentive: A triangular architectural feature that provides a smooth transition between the circular base of a dome and the square bay formed by its four supporting piers.

perspective drawing: A technique for representing a three-dimensional scene on a two-dimensional surface in a way that accurately depicts spatial depth. Also called linear perspective.

pick: In weaving, one pass of the weft thread through the warp threads mounted on a loom.

pier: A heavy column that provides structural support for a building or bridge.

pig iron: Cast iron produced by a blast furnace.

pike: A weapon consisting of a long wooden shaft with a pointed steel head.

pile: A wooden foundation element, driven into the ground to provide structural support.

pipe flow: In fluid mechanics, a type of flow in which the fluid completely fills the pipe or conduit and is driven by internal pressure.

pitch: The slope of a roof.

pitched pavement: A pavement created by setting flat stones on edge in a bed of mortar on top of a base layer of compacted sand.

plain weave: A type of cloth created by passing the weft thread alternately over and under successive warp threads.

plastic deformation: The permanent deformation of a material under load.

platen: In Gutenberg's printing system, a screw-driven plate used to press the paper onto the form to create a printed impression.

point: One subdivision of the mariner's 32-point compass. One point equals 11.25°.

portcullis: A heavy, movable wood-and-iron grid used to block entry through the gateway of a castle or fortified city. A portcullis is raised and lowered by an overhead windlass.

post-mill: An early vertical windmill, developed in Europe during the late 12th century.

potential energy: The energy associated with an elevated mass.

power: The rate at which work is done (i.e., work per unit of time).

pulley: A simple machine that changes the direction of a rope without significantly changing the tension in the rope.

purlin: A longitudinal beam in a timber roof system.

quadripartite vaulting: A vault configuration with four compartments per bay.

quatrefoil: A Gothic decorative element consisting of four round lobes oriented perpendicular to each other.

quenching: A heat-treating process in which a heated metal is plunged into cold water or oil. When applied to iron or steel, quenching strengthens the metal but also causes it to become brittle.

rafter: An angled beam that supports a roof.

ratchet: A device—typically consisting of a toothed wheel and a lever—that allows rotation in one direction but prevents rotation in the opposite direction.

refectory: The dining hall of a monastery.

refraction: The tendency of light rays to bend when they pass from one medium into another.

Renaissance: The period from the 14th to the 16th century, when Europeans experienced a revival of interest in the literary and artistic values and forms of classical antiquity.

ribauldequin: A gunpowder weapon that used multiple barrels mounted on a single carriage.

ribband: A flexible board used to work out the geometry of a hull form in early carvel (frame-first) ship construction.

ridge beam: A longitudinal beam that supports the peak of a roof.

right-angle gearing: An assembly of two gears that transmit mechanical power from a rotating shaft to a perpendicular shaft.

ringwork castle: A simple fortification usually consisting of a ditch, earthen rampart, and wooden palisade arranged in a circle or oval.

rod: A medieval unit of measurement equal to 16½ feet.

rotary quern: A hand-operated device used to mill grain by rotating one stone (the runner) over another (the bed stone).

rotational inertia: The tendency of a rotating mass to continue rotating.

roving: A bundle of parallel fibers, used in the process of spinning fibers into thread.

runner: The upper rotating stone in a pair of millstones.

running: Sailing in the same direction as the wind is blowing.

running rigging: On a sailing ship, rigging that is used to control the yards and sails.

sagging: The bending of a ship's hull caused by large waves fore and aft and a trough amidships. A sagging hull bends concave upward.

saltpeter: A naturally occurring waste product of decomposing organic material.

sapper: A soldier employed in building structures and applying tools to enhance the protection and mobility of a military force.

scaling ladder: In siegecraft, a ladder used by assault troops to climb to the top of an enemy wall.

schiltron: A traditional Scottish infantry formation in which multiple ranks of infantry wielding long pikes were formed into a square that could defend itself against an attack from any direction.

screw: A simple machine that converts a rotational force (or torque) to a linear force.

segmental arch: An arch, the shape of which is a segment of a semicircle.

self-bow: A bow made from a single piece of wood.

selion: A long, narrow strip of agricultural land within a medieval manor.

semidome: A half dome.

serf: An unfree peasant who served as a tenant farmer on a medieval manor. Serfs were bound to the land on which they worked.

sexpartite vaulting: A vault configuration with six compartments per bay.

shaft: In weaving, a movable frame on which heddles are mounted. The frame is repositioned to create a shed, through which the weft thread is passed.

shearing: A type of material failure in which an applied force causes one portion of a crystal lattice to slide with respect to another along a failure plane.

shed: In weaving, a triangular opening between two sets of warp threads. During the weaving process, the weft thread is passed repeatedly back and forth through the shed.

sheet: On a sailing ship, an element of the running rigging that is used to control a lower corner of a sail.

shell-first construction: A shipbuilding technique in which the outer shell of a hull is assembled first, using edge-joined planks. Internal frames are then added to strengthen the hull.

shroud: On a sailing ship, an element of the standing rigging that provides lateral support to a mast.

shuttle: In weaving, a boat-shaped device that holds a supply of thread for the weft.

siegecraft: The art and science of gaining entry into a fortified place, often through the use of specialized machines.

skin friction: A type of water resistance caused by water flowing across the submerged surface of a hull.

slag: A waste material produced during the smelting of ore into usable metal.

sluice gate: A gate that can be raised or lowered to control the flow of water from a reservoir into a channel.

smelting: The process of heating an ore to remove impurities and produce a usable metal.

sort: One piece of reusable type in a printing system.

spandrel: The triangular space above an arch, normally filled with solid masonry.

spanning: The process of cocking a crossbow.

spillway: A dam component that allows excess water to overflow from a reservoir.

spindle: The iron pivot on which a millstone rotates.

springald: An arrow-shooting torsion catapult developed in the 13th century.

spur gear: A gear with radially oriented teeth in the same plane as the gear.

square-rigged ship: A sailing ship propelled by one or more rectangular sails.

standing rigging: On a sailing ship, rigging that supports the mast(s).

stave construction: A traditional Nordic timber construction method consisting of vertical posts, horizontal sills, wall plates, and solid walls composed of tongue-and-groove planks (staves).

stay: On a sailing ship, an element of the standing rigging that provides fore-and-aft support to a mast.

steel: An alloy of iron and carbon, with more than 0.1% and less than 2% carbon by weight.

sternpost rudder: A rudder mounted centrally at the stern of a ship.

stilt: The handle of a plow.

stilting: In architecture, the practice of elevating the short-spanning arches of a rectangular vault, so the tops of their associated vault compartments will be at the same elevation as those of the long-spanning arches.

strake: In shipbuilding, a plank that runs for the full length of a hull.

strength: The maximum load or stress a material can carry before it breaks.

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

stringer: A longitudinal beam that supports a floor or deck.

structure: A technological system—typically a building, bridge, or tower—that is designed to carry load.

tacking: A sailing maneuver in which the ship turns its bow through the wind in order to receive the wind on its opposite side. By executing this maneuver repeatedly, the vessel can make progress directly into the wind along a zigzag path.

tailpole: A long, heavy beam that extends from the rear of a windmill and is used to turn the rotor into the wind.

tailrace: An artificial channel that carries water away from a waterwheel.

tang: The rearward extension of a sword blade, on which the cross guard, pommel, and grip are mounted.

tapestry: A plain-woven weft-faced textile depicting a pattern or pictorial design and typically used as a wall hanging.

tas-de-charge: An architectural feature at which the bottom ends of multiple arches and ribs appear to merge together as they converge on a column or pier.

technology: A structure, device, machine, system, or process that meets a human need. Technology is the product of engineering.

tempering: A heat-treating process in which the ductility of iron or steel is improved by heating the metal to a moderate temperature and then allowing it to cool slowly in air.

tension: An internal force or stress that causes a structural element to elongate.

terra-cotta: A ceramic material created by firing clay in a kiln to improve its strength and durability.

three-field crop rotation: An agricultural system in which a parcel of land is subdivided into three fields. In any given year, two fields are cultivated, while the third is left fallow to recover its fertility.

thrust: The tendency of an arch or dome to spread outward under load.

tidal mill: A mill that uses the potential energy associated with a coastal body of water at high tide to produce mechanical power.

tie beam truss: A truss that uses a single horizontal member—the tie beam—to connect its two ends together.

tiller: The wooden stock of a crossbow.

torque: The tendency of a force to cause rotation. Torque is expressed in units of force times distance.

torsion: The twisting of a structural or mechanical element.

torsion catapult: An artillery weapon that uses one or two torsion springs to throw stones or bolts.

torsion spring: A spring consisting of a twisted bundle of rope, typically made from animal tendons.

tower mill: A type of windmill that was developed in the late 13th century and incorporated significant mechanical improvements over the post-mill.

***trace italienne*:** A system of fortification design developed in the early 16th century to provide improved defense against gunpowder artillery.

transept: One of two wings or extensions that are arranged perpendicular to the nave in the floor plan of a cruciform building. The transepts intersect with the nave at the crossing.

treadle: A foot pedal used to actuate a machine or a mechanical component.

treadwheel: A device for harnessing and amplifying human power in construction cranes and similar machines.

trebuchet: A medieval siege catapult powered by either a large counterweight or a team of men pulling on ropes. The latter is called a traction trebuchet or mangonel.

triforium: An arcaded gallery located at the second level of a Gothic cathedral. Some Romanesque cathedrals also have a triforium.

trip-hammer: A machine that provides repetitive pounding through the use of a camshaft.

trireme: A rowed warship with oars on three levels.

trunnion: A cylindrical projection used to support a cast cannon barrel on its carriage.

truss: An assemblage of structural members arranged in interconnected triangles to form a rigid framework.

turning bridge: A type of drawbridge that uses a counterweight at its inner end to reduce the pulling force required to lift the bridge.

tuyere: A pipe through which air is blown into a furnace or forge.

twill weave: Cloth created by passing the weft thread alternately over or under multiple warp threads in each pick.

two-field crop rotation: An agricultural system in which a parcel of land is subdivided into two fields. In any given year, one field is cultivated, while the other is left fallow to recover its fertility.

tympan: In Gutenberg's printing system, a cloth pad used to support and protect the printed page.

tympanum: A wall that fills the interior space within an arch.

undershot waterwheel: A waterwheel that is mounted on a horizontal shaft and is driven by water passing underneath the wheel.

vanishing point: In perspective drawing, a point on the horizon at which receding parallel lines appear to converge.

vault: An arched structural element that is used to enclose space.

verge-and-foliot: An escapement consisting of a horizontal bar (the foliot) fixed to a vertical rod (the verge) with two appendages (pallets) that engage alternately with a toothed wheel (the crown wheel) to regulate the fall of a weight.

vertical warp-weighted loom: A type of loom that uses suspended weights to hold the warp threads in tension during the weaving process.

voussoir: A wedge-shaped stone used to build an arch or vault.

wale: A thick plank that adds strength and stiffness to the hull of a ship.

wall plate: A horizontal structural element that transmits the weight of a roof structure downward into the supporting wall.

wallower: In a windmill, the small lantern pinion (gear) that transmits mechanical power from the brake wheel to the machinery within the mill.

warp: In weaving, a set of parallel threads mounted on a loom and stretched in tension.

waterpower: Mechanical power produced from the energy in flowing water.

wave-making drag: A type of water resistance caused by a ship's hull pushing displaced water sideways as the hull moves forward.

weather helm: The tendency of a ship sailing across the wind to turn into the wind.

weaving: The process by which two perpendicular sets of thread or yard are interlaced with each other to create cloth.

weaving sword: A device used to compact each new pick into position in woven cloth.

web: A thin stone shell that fills the space between two adjacent ribs in ribbed groin vaulting.

weft: In weaving, a set of parallel threads that are interlaced through the warp threads to create cloth.

weir: A damlike structure built across a river or stream to raise the water level and, in some cases, to divert the flow into a canal, headrace, or other artificial channel.

whorl: A weighted disk mounted at the top or bottom of a drop spindle.

windlass: A device for harnessing and amplifying human power to pull a rope. A windlass typically has a horizontal shaft, while a capstan has a vertical shaft.

windshaft: The shaft on which the main rotor of a windmill turns.

***wipmolen*:** A specialized type of windmill developed in the Netherlands for the purpose of draining wetlands for land reclamation.

wootz steel: A type of high-quality steel produced primarily in southern India, using a specialized process that involved heating a particular type of iron ore together with a source of carbon inside a sealed crucible.

work: The quantity of energy transferred when a force moves through a distance.

wrought iron: Iron produced by the bloomery process. Wrought iron typically has less than 0.1% carbon content by weight.

yard: On a sailing ship, a horizontal or diagonal spar from which a sail is suspended.

yoke: A wooden beam fitted over the shoulders of a draft animal to facilitate pulling a load.

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