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THOMAS J. MISA

Leonardo

TECHNOLOGY & CULTURE

FROM THE RENAISSANCE TO THE PRESENT

to the Internet

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PREFACE

IN THIS BOOK I explore the varied character of technologies in the West over the half-millennium from the Renaissance to the present. The investigation spans the preindustrial past; the age of scientific, political, and industrial revolutions; and on to more recent topics, such as imperialism, modernism, war, and global culture. That particular span of time seems well suited to provide a solid empirical base for exploring the wide-ranging notions about technology that I consider in the final chapter.

This study began more than a decade ago when I was trying to understand the work of Leonardo da Vinci. A little background reading convinced me that the time-honored image of Leonardo as an artist and anatomist, who did some nice-looking technical drawings on the side, just did not capture his life. Leonardo spent his most active years working as a technologist and engineer. It is scarcely an exaggeration to say that his famous paintings and strikingly realistic anatomical drawings were done in the periodic lulls between his technology projects. I puzzled further over the character of Leonardo's technical work. Was he really, as some enthusiasts claimed, the "prophet of automation," the inventor of labor-saving machines (and such wonders as helicopters, airplanes, and automobiles) that catapulted Europe from the "dark ages" directly into the modern era? Thinking about these questions, I began to see a distinctive focus in Leonardo, and in the numerous engineers with whom he shared notebook drawings and technical treatises. The technological activities of these Renaissance engineers related closely to the concerns of the Renaissance courts and city-states that commissioned their work. I failed to find Leonardo much concerned with labor-saving or "industrial" technologies, and for that matter few of his technological projects generated wealth at all. Quite the opposite. Leonardo's technologies were typically wealth-*consuming* ones: the technologies of city building, courtly entertainments and dynastic display, and war making.

The Renaissance court system was the conceptual key. While it is common knowledge that Johann Gutenberg invented the Western system of moveable type printing, it is not well known that he himself was a court pensioner. Printing shops throughout the late Renaissance depended, to a surprising extent, on court-generated demand. Even printed books on technical subjects were objects of courtly patronage. I began to appreciate that Renaissance courts across Western Europe, in addition to their well-known support of famous artists, scientists, and philosophers, were at the time the dominant patrons of the most prominent technologists. These courts included royal courts in Spain and France, ambitious regional rulers in Italy, the papal court in Rome, and court-like city-states such as Florence and Milan. The technical projects they commissioned, from the Florence cathedral to the mechanical robots for courtly entertainment, as well as the printed works on science, history, philosophy, religion, and technology, created and themselves constituted Renaissance culture. This heady mix of technology, politics, and culture is the subject of chapter 1.

There are good reasons to see the industrial revolution as a watershed in world history, but our time-worn inclination to seize on industrial technologies as the only ones that really matter has confounded a proper understanding of the great commercial expansion that followed the Renaissance. Chapter 2 discusses these developments. Economic historians persistently ask the same questions about the great Dutch Golden Age in the seventeenth century: How fast did the Dutch economy grow, and why didn't it industrialize? The Dutch not only had rising per capita incomes and a healthy and diverse national economy; they were also the architects and chief beneficiaries of the first multicentered global economy. Again, on close inspection I found a distinct character in Dutch technological activities. Commerce, like the courts, fostered distinctive but nonindustrial technologies. Dutch merchants and engineers were highly attuned to generating wealth and took active steps to sharpen their focus on making high-quality items with relatively high-paid labor. The typical Dutch cloth was not cheap cotton—the prototypical industrial product—but high-priced woolens, linens, and mohairs. Dutch technologies formed the sinews for that country's unprecedented international trading system, which included shipbuilding, sugar refining, instrument making, and innovations in finance, like joint-stock companies and stockmarkets. I began not only to think of technologies as located historically and spatially in a particular society and shaped by that society's ideas of what was possible or desirable, but also to see how these technologies evolved to shape the society's social and cultural developments. To capture this two-way influence, I took up the notion of distinct "eras" of technology and culture as a way of organizing the material for this book.

This notion of distinct eras provides a kernel for new practical insight into our own social and cultural prospects. My view on technology argues against the common billiard-ball model propounded by many popular writers and journalists who see technologies coming from "outside" society and culture and "impacting" them—for good or ill. Indeed, the question whether technologies are outside a society or within it is a far from trivial matter. If technologies come from outside, the only critical agency open to us is slowing down their inevitable triumph—a rear-guard action at best. By contrast, if technologies come from *within* society and are products of on-going social processes, we can, in principle alter them—at least modestly—even as they change us. This book presents an extended empirical evaluation of this question. It shows, in many distinct eras, historical actors actively choosing and changing technologies in an effort to create or sustain their ideas of a good life or desirable social and cultural developments (whatever these happened to be).

With these issues in mind, I came to the industrial revolution in Britain with a new interest in comprehending "industrial society," which I explore in chapter 3. An older view—that the industrial revolution radically transformed Britain in the few decades around 1800 and soon thereafter forcibly propelled the world into the modern age—has just not stood the test of time. This version of the billiard-ball model of how technology changes society is, in its simple one-way formulation, empirically false. In the last two decades or so, historians have learned too much about the vast range of historical experiences during industrialization and the dynamics of industrial change and economic growth to sustain the older view of the industrial revolution. For example, we know now that surprisingly few industrial workers in industrial Britain actually labored in large-scale factories (only about one worker in ten) and that there were simply too few steam engines to do anything like "transform" the entire economy—until well into the nineteenth century.

In a convulsion of skepticism and debunking, historians have all but thrown out the concept of an industrial revolution. I would like to revive it, for I think we can see a distinct and historically specific logic that shaped technologies during the early industrial revolution. In industrial era Britain there were precious few Dutch-style technologists focusing on high-quality materials and high-paid labor. Instead, the predominant focus of British technologists was, let's say, industrial: cutting costs, boosting output, and saving labor. Inventions of the era embodied these socioeconomic goals. Cheap cotton cloth, and lots of it, made by ill-paid factory "hands," was a representative product of industrial-era Britain. If mechanizing industry was not the highest calling in life, as Victorian moralists repeatedly warned, it was nevertheless a central and defining purpose for inventors, engineers, and industrialists of the time. Beyond Britain, commentators and technologists sometimes looked to copy British models of industry but more frequently adapted industrial technologies to their own economic and social contexts. The result was a variety of paths through the industrial revolution.

Given these ideas about court, commerce, and industry as defining purposes for technology, I began thinking more broadly about what helped define technologies in the next two centuries—closer to home, as it were. The task became more difficult. It was impossible to isolate a single distinct "type" of society with a corresponding set of technologies. The legacy of the industrial revolution, it seemed, was not a single "industrial society" with a fixed relationship to technology but rather a multidimensional society with a variety of purposes for technology. Between the middle decades of the nineteenth century and the early decades of the twentieth, at least three varied purposes of technology can be identified—the themes of chapters 4, 5, and 6.

The first of these technology-intensive activities to fully flower was empire building, the effort by Europeans and North Americans to extend economic and political control over wide stretches of land abroad or at home. This is the subject of chapter 4. Imperialists faced unprecedented problems in penetrating unfamiliar lands, often in the face of determined resistance by native peoples, and in consolidating military and administrative control over these lands and their peoples. Steamships, telegraphs, and transcontinental railroads were among the technologies that made imperialism effective and affordable. The "gunboat diplomacy" deployed by the British with great success in China, India, and Africa against poorly armed native peoples depended on the construction of iron-hulled, steam-driven, shallow-draft vessels that were heavily armed. (Also in the mid-nineteenth century, and in parallel with steamboats, the use of quinine gave Europeans for the first time reasonable odds against endemic malaria in Africa and Asia.) It would be foolish not to recognize the economic dimensions of the imperialist venture, since Britain's factory-made

cotton textiles were shipped off to captive markets in India to be exchanged for tea and raw cotton (with a side trade in opium).

All the same, more was at play during the imperial era than just the disposing of surplus factory goods or the importing of cheap raw materials, important though these were. No one at the time tried to justify or defend empire in strictly economic terms. Feelings of national and imperial pride, the presumed imperatives of linking colonies to the homeland, the often-bizarre economics of empire (where for instance tremendously expensive steamboats or railroads "saved" money in transporting military forces or colonial officials)—these were the ways Britain's imperialists coaxed from taxpayers money for such extravagant ventures as the round-the-world telegraph system, easily the most demanding high-technology effort of the nineteenth century. Long-distance repeating telegraphs, efficient coal-burning steamships, and undersea telegraph cables tempted imperial officials to exert oversight and control over far-flung possessions. Many imperialists credited the telegraph network with "saving" British rule in India during the Mutiny of 1857–58. The same reasoning—national pride, imperial imperatives, and the economics of empire—helps explain the urgency behind the transcontinental railroads in India, North America, and South Africa. Economics as traditionally understood had little to do with empire or imperial-era technologies.

A second impulse in technology gathering force from the 1870s onward lay in the application of science to industry and the building of large systems of technology, the subject of chapter 5. For the first time, in the rise of the science-based chemical and electrical industries, scientific knowledge became as important as land, labor, and capital as a factor of production. The new importance of science led to the rise of fundamentally new social institutions: research-based universities (universities *per se* were centuries old), government research institutes, and industrial research-and-development laboratories, all of which appeared on a large scale in Germany before 1900 and in the United States a little later. The rise of the chemical, electrical, steel, and petroleum industries, and the associated large corporations that funded and managed them, constituted a second industrial revolution. Britain, the first industrial nation, played a surprisingly small role in the movement.

In chapter 6 I examine the intense interactions between modern technology and modern aesthetics during the first half of the twentieth century. This inquiry clarifies the ways technology in the twentieth century formed not only the backdrop of our economy but also the foreground of our daily lives. The twentieth-century modern movement was built on technological capabilities developed during the science-and-systems era, and yet it led to new and distinctive cultural results. The achievement of mass-produced steel, glass, and other "modern materials" around 1900 reshaped the aesthetic experience of working or walking in our cities and living in our homes. These modern materials were the precondition and artistic inspiration for the modern movement in art and architecture that flourished between 1900 and 1950. Modernism led to avant-garde designs for public-housing blocks and office buildings as well as museums, hospitals, and schools. The movement, through its association with German household reformers and with New York's Museum of Modern Art and other self-appointed arbiters of "good taste," shaped public fascination with new modernist designs for domestic appliances.

The book's middle chapters, besides setting down some engaging stories, advance my argument concerning the "question of technology." Highly articulate figures—the artists, architects, and household reformers of the modern movement—self-consciously embraced technology to achieve their visions of housing the poor, embracing modern urban life, and what they saw as enhancing modern society's cultural and spiritual development. Even if you find the modernists' enthusiasm for technology a bit naïve today, you must allow that they both shaped specific technologies and conditioned cultural developments. Mine is not a relentlessly optimistic worldview. In these middle chapters you will also find industrial technologies implicated in the conditions of filthy, disease-ridden cities and imperial technologies implicated in the slaughtering of natives in India and North America. Technology has been and can be a potent agent in disciplining and dominating. I also discuss the modernists' troubling embrace of a fixed "method" of creativity.

My thinking on this book began during the waning days of the Cold War. Since then, it has become easier to see clearly how important the superpowers' military services were in finding and funding technologies of real or imagined military utility. The "command economies" that took shape during World War II fanned the development of countless technological innovations, of which atomic power, radar, and computers are only the best known examples, as chapter 7 recounts. In the Cold War decades, scientists and engineers learned that the military services had the deepest pockets of all potential technology patrons. For dreamers and schemers of the most massive technology projects, the military was the

main chance. The story is told of the Nazi rocket scientist Wernher von Braun preparing his laboratory for surrender in the chaotic closing days of World War II. "Most of the scientists were frightened of the Russians, they felt the French would treat them like slaves, and the British did not have enough money to afford a rocket program. That left the Americans."[1]

It is worth recalling the social and political changes brought about during the military-dominated era of technology. In all the great powers during the Cold War era, state-imposed secrecy pervaded the weapons, aerospace, nuclear, and intelligence sectors. (With the opening of archives we have learned how shockingly similar were the Soviet, American, and French nuclear technocrats, sharing kindred visions of limitless energy, technology-induced social change, and at times contempt of safety concerns, even as they were divided by great-power rivalries.) In the United States the fortunes of research universities like MIT and Stanford and industrial contractors like Bell Labs, Boeing, RCA, IBM, and General Electric depended to a surprising degree on the Pentagon. With the end of the Cold War, the sharp contraction of military research and development budgets traumatized technology-based companies, universities, and government institutes.[2] In the West we are comparatively lucky. In the former Soviet Union, frighteningly enough, high-level nuclear technicians with ready access to dangerous materials have been told in no uncertain terms to find work elsewhere.

The hardest history to write is that of our own time, and yet I believe that "globalization," or "global culture," is a force that oriented technology and society in the final three decades of the twentieth century. This is the topic of chapter 8. Think about the world as recently as 1970, without pervasive fax machines, automatic teller machines, and cellular phones. Take away ready access to email and the Internet and bring back the library's card catalogue. Hike the charge fifty-fold for an overseas telephone call. Do away with NASDAQ, Microsoft, Dell Computer, and Amazon.com. Make it impossible for a middle-class Western person to invest retirement savings in anything but domestic government bonds. For that matter, keep the faith that a foreign takeover of the company you work for is impossible. Now ease your way back into the current world. Where an after-hours phone call to a Texas bank is likely to be answered by a call-center worker in India. Where anyone with an Internet connection can risk a stock investment in the Finnish cellular-phone giant Nokia. Where Daimler owns Chrysler and Bertelsmann owns Random House; where Disney owns a choice piece of Paris, and where McDonald's owns a small slice of everywhere. No wonder that the coming of a global culture has brought both exhilaration and fear.

The intellectual framework set out in this book is necessarily tentative, really a way of thinking about our relationships with technology and the perennially puzzling "question of technology," to which I return in the final chapter. Yet, by adopting this way of thinking, several perplexing observations about technology can be brought into sharper focus. At least since Alvin Toffler's best-selling *Future Shock* (1970) pundits perennially declare that the pace of technology is somehow quickening and that technology is forcing cultural changes in its wake, that our plunge into the future is driven by technology gone out of control. The evidence cited for these conclusions is invariably Moore's Law, an observation of electronics pioneer Gordon Moore that every eighteen months the speed of computer chips doubles. I appreciate the obvious difference between my first, stand-alone Macintosh from 1984 and my present networked computer that can process words, images, sounds, and movies—and in its off hours aid the search for extraterrestrial intelligence.[3] And it is mind-boggling that the number of transistors manufactured each year now exceeds the number of individual *letters* printed each year in books, newspapers, and magazines.

All the same, I'd like to propose Misa's Corollary to Moore's Law. My corollary states that the size of computer operating systems and software applications has doubled *at the same pace* as the operational speed of computer chips, soaking up the presumed power of the hardware and blunting its impact. Here is some evidence for my proposition: my present vintage-2000 word-processing program takes up fully 1,000 times the disk-storage space as did my vintage-1985 one, even though both feature pull-down menus and a graphics-friendly display, fancy fonts and formatting, and many other features. For fifteen years, amazingly enough, the program has doubled in size each and every eighteen months. My computer operating systems have also doubled in size each eighteen months; it would take no less than 1,000 old-style floppy disks to store the latest monstrous-sized one. Because of its so-called bloatware, my present computer—despite its many megahertz central-processing unit—takes much longer to start up than does my vintage-1984 machine. The same for launching the respective word processing programs. (This is a genuine puzzle to me. Except for the surreptitious "Easter eggs," or unauthorized computer code that programmers embed as inside jokes [see

www.eeggs.com], I have been unable to locate any sensible explanation for the excesses of this bloatware.) Overall, I am doubtful that computing chips alone can help us comprehend the perception of an increasing pace of change, which reaches back at least to the "Science Holiday" movement of the 1930s that sought to ban science-induced technological changes precisely because of their disruptive social and economic consequences.

Instead of a crude technological determinism derived from Moore's Law, I would trace our perception of quickening to a split between our normative expectations for technology and what we observe in the world around us. It is not so much that our technologies are changing especially quickly but that our sense of what is "normal," about technology and society, cannot keep pace. We know that regulatory laws cannot keep up with the practices of cyberspace, that ethical norms are challenged by cloning and biotechnologies, that our very identities are created and constituted by surveillance technologies as well as cell phones, and that scarcity-based economics may be entirely overthrown by nanotechnologies.

In this regard, the longer-duration "eras" of technology discussed in this book can be interpreted as a deep foundation for our cultural norms. These eras appear to be shortening: the Renaissance spanned nearly two centuries, while the twentieth century alone saw the eras of science and systems, modernism, war, and global culture. It is worth mentioning a quickening also in the *self-awareness* of societies—our capacities to recognize and comprehend change are themselves changing. While the Renaissance was not named until two centuries after the fact (in the 1830s) and the term *industrial revolution* became part of the English language a half-century after the Manchester region had dozens of huge factories, the telephone, invented in 1876, took exactly one decade to register culturally. Just four years after Moscow's first telephone station opened, Anton Chekhov published a short story "On the Telephone" (1886), about a hapless early user trying to make a restaurant reservation with the new machine. By comparison, the notion of "cyberspace" arrived in the 1980s with William Gibson's science fiction novel *Neuromancer* almost before the fact of cyberspace. This self-awareness of major historical change is clearly an instance of "reflexive" modernization in sociologist Ulrich Beck's sense. In this way, then, these eras do capture something real in our historical experience.

Finally, while this book traces a long history from Leonardo to the Internet, it in no way argues "the triumph of the present." Indeed, I am pretty sure that our next generation's relationships with technology will *not* be identical to our recent one, although in what ways they may be different is risky to prophesy. Indeed, this work has found its mark if it prompts readers to open up a mental space for thinking both more widely and more deeply about technology. I would hazard the guess that the perceived quickening of the pace of change will continue, and as a citizen I hope that we will be able to channel technology toward socially productive purposes. We face immense challenges in climate change, international development, and economic disparities, as well as in many other areas, and these challenges have not engaged the potential of the world's technologists. This is a pity. I hope that readers, by the end of this book, will understand the complex reasons why this is so. In a nutshell, it goes like this. Societies, pursuing distinct goals and aspirations, have chosen and sustained certain technologies; and these technologies have powerfully molded their economic, social, and cultural capabilities. What type of society we wish for the future is at once an open question and a constrained choice. While our societal debate must be an open one, accessible by all members, practically speaking our choices about our society's tomorrow will be framed by the choices we make about our technologies today.

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Finally, I would like to dedicate this book to the memory of my father, Frank Misa, who was born in the last years of the science-and-systems era, grew up in the era of modernism, lived through the era of war, and glimpsed the possibilities of global culture. He would be pleased that I now have a bit more time for backyard games of basketball with Henry and Christopher and leisurely walks with Ruth.

Leonardo to the Internet

1

TECHNOLOGIES OF THE COURT

1450–1600

EVEN RENAISSANCE MEN struggled with their careers. Niccolò Machiavelli, acclaimed as a political philosopher, and Leonardo da Vinci, hailed as a universal genius, saw tough times during these turbulent years in Italy. Machiavelli (1469–1527) grew up in Florence when it was under the control of Lorenzo de' Medici, who ruled the city-state by what we might now call cultural machine politics. Florence was nominally a republic governed by committees elected from its six thousand guild members. But during the long decades of Medici rule, uncooperative committees were disbanded, while the family created and wielded effective power through an elaborate network of cultural patronage, financial preferences, and selective exile. A Medici-inspired vogue for showy urban palaces, lavish rural villas, and prominent churches, convents, and monasteries kept Florence's artists and builders busy—and the Medici coat of arms embedded in the family's numerous buildings kept its citizens ever mindful of the benefits of Medici rule. Machiavelli's two-decade-long public career, serving his beloved but rickety republic, lasted only so long as the Medici dynasty was out of power.[1]

The Medici dynasty in power was more important for Leonardo da Vinci (1452–1519). Leonardo did his apprenticeship in Medici-ruled Florence, worked then and later on projects sponsored by the Medici, and launched his career with the blessing of the Medici. Whether from the Medici family or from his numerous other courtly patrons, Leonardo's career-building commissions were not as a painter, anatomist, or visionary inventor, as he is typically remembered today, but as a military engineer and architect. Courtly patrons, while offering unsurpassed fame and unequaled resources to the artists, philosophers, architects, and engineers they deemed worthy, did not guarantee them lifetime employment. The Medici's return to power brutally ended Machiavelli's own political career. He was jailed and tortured, then in forced retirement he wrote his famous discourse on political power, *The Prince*, which was dedicated to the new Medici ruler in an unproductive hope of landing a job.

Political turmoil in the court system shaped Leonardo's career as a technologist just as decisively. In 1452, the year of his birth, the city-states of Italy were gaining economic and cultural prominence. Venice had long dominated medieval Europe's trading with the Near East, Florence was flourishing as a seat of banking and finance, and Rome doggedly asserted the primacy of the pope. The princely dominions of Milan and Urbino were ruled outright by noble families, who dispensed artistic and cultural patronage even more lavishly. Leonardo's career was so wide-ranging (he worked at each of these five locations) because the era was politically unstable. And the era was unstable because military conflict was never far away. Rulers up and down the Italian peninsula found themselves at every turn confronting hostile forces: to the east it was the Ottoman Turks, to the north loomed assertive France, and across the peninsula they battled among themselves for valuable land or strategic ports or dynastic advantage. Military engineers such as Leonardo were much in demand. During these decades, secular and religious powers melded uneasily. What else can we say of the cardinals of Rome electing as pope a worldly member of the Borgia family who, at his court, openly showed off his mistress and their four children?

Whether secular or religious, Renaissance courts and city-states had expansive ambitions, and technical activities figured prominently among their objects of patronage. The history of Renaissance technology is typically told as a story of individual engineers such as Leonardo da Vinci, Francesco di Giorgio, and others, as if they worked as independent free agents; and the history of Renaissance politics and culture is typically related to the shifting fortunes of the varied city-states and noble courts and individuals, like Machiavelli. We will see, however, that technology, politics, and culture were actually never far apart. For a time, thoroughly mixing these domains, Machiavelli and Leonardo even collaborated on a grand engineering plan to improve the commercial and military prospects of Florence by moving its river.

This chapter locates Renaissance technologists squarely within the system of court patronage. We will see that the papal court in Rome sponsored or employed such landmark technological figures as Alberti, Leonardo, and Biringuccio. Leonardo's career as an engineer is inseparable from his work for the Medici family, the Sforza court, and the Borgia clan. The pattern of court-sponsored technologies extended right across Europe (and for that matter beyond Europe[2]). Royal courts in France, Spain, and England supported innovations in shipbuilding and silk weaving. Even the well-known history of moveable-type printing needs to be reexamined in the light of pervasive court sponsorship of technical books and surprisingly wide court demand for religious publications. Characteristically, Leonardo and his fellow Renaissance-era technologists had surprising little to do with improving industry or making money in the way we typically think of technology today. Instead, Renaissance-era courts commissioned them for numerous technical projects of city-building, courtly entertainment, and dynastic display, and for the means of war. As one Leonardo scholar observes, "It was within the context of the court that the engineer carried out his many duties, first and foremost of a military nature."[3]

The Career of a Court Engineer

The practical world of artisans that nurtured Leonardo as a young man was far removed from the educated world of courtly scholars such as Machiavelli. In the absence of biographical writings, we must guess at much of Leonardo's early life. Documents recording legal disputes with his stepbrothers make it clear that he was the illegitimate son of a low-level lawyer, and that he was raised by his paternal grandparents. The clarity of his handwriting points to some formal education, while a desire to hide his inventions from prying eyes is suggested by his famous backwards or "mirror" writing. At the age of fourteen he was apprenticed in the Florence workshop of sculptor and painter Andrea del Verrocchio. While Italy's thriving universities were the sites for educating scholars, workshops such as Verrocchio's served as the principal sites for educating artisans and craftsmen. In his decade with Verrocchio (1466–76) Leonardo learned the basics of architecture, sculpture, bronze casting, painting, and possibly some mathematics. During these years, Verrocchio had several major commissions, including an ostentatious family tomb for the Medici and a large bronze statue commemorating a Venetian military hero.

As a member of Verrocchio's workshop, Leonardo had a small but visually prominent role in building the Florence cathedral. Officially the Cathedral of Santa Maria del Fiore, it was described by one contemporary as an "enormous construction towering above the skies, vast enough to cover the entire Tuscan population with its shadow . . . a feat of engineering that people did not believe feasible . . . equally unknown and unimaginable among the ancients" (fig. 1.1). In 1420, more than a century after the cornerstone was laid, Filippo Brunelleschi (1377–1446) gained the city's approval for completing its impressive dome and began work. Brunelleschi's design followed the official plans for an eight-ribbed dome, more than 100 feet high, which began 170 feet above the cathedral's floor. The dome measured 143 feet in diameter—then and now the largest masonry dome in the world. Brunelleschi directed that the dome's lower level be built of solid stone and its upper levels consist of a two-layered shell of stone and brick; at its apex stood a 70-foot-high lantern tower to admit light and air. To construct this novel structure, without wooden bracing from underneath, Brunelleschi devised numerous special cranes and hoisting apparatuses that could lift into place the heavy stones and bricks. Brunelleschi, often with Cosimo de' Medici's support, designed numerous other buildings in Florence, including the Ospedale degli Innocenti, a charitable orphanage commissioned by the silk merchants guild which is notable as an early and influential example of a distinctive Florentine style of architecture. Although the cathedral's dome and lantern had been completed (in 1461) before Leonardo came to Florence, there remained the difficult task of placing an 8-foot-high copper sphere at its very top. Verrocchio's workshop built and finished the copper sphere and, using one of Brunelleschi's cranes that was still in service, placed it to stand a dizzying 350 feet above the city's streets.[4]

The cathedral project occupied Verrocchio's workshop from 1468 to 1472 and made a distinct impression on the young Leonardo. Forty years later he wrote, "Keep in mind how the ball of Santa Maria del Fiore was soldered together."[5] At the time Leonardo made numerous drawings of the varied hoisting machines that Brunelleschi had designed to lift the heavy stones, of the revolving crane used to position them, and of several screwjacks and turnbuckles. In addition to his work as an architect and sculptor, Brunelleschi was a pioneer in geometrical perspective (discussed below), especially useful in capturing the three dimensionality of machines in a two-dimensional drawing. From Leonardo's notebooks it is clear that he mastered this crucial representational technique. To depict Brunelleschi's heaviest hoisting machine, an ox-powered, three-speed winch with a system of reversing ratchets that allowed workers to raise a stone and then carefully lower it into place without physically reversing

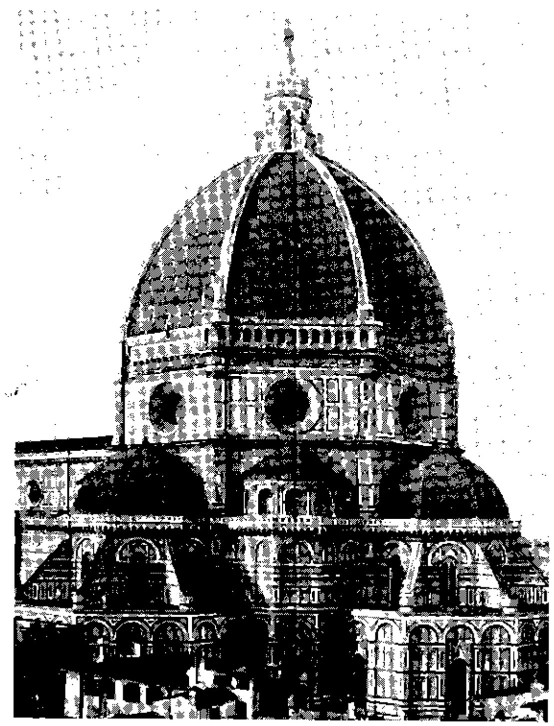

FIG. 1.1. Dome of the Florence Cathedral.

Renaissance-era building projects frequently mobilized advanced technology to create impressive cultural displays. To complete the Florence cathedral Brunelleschi erected the largest masonry dome in the world, measuring 143 feet in diameter. The octagonal, ribbed dome was formed in two layers, using bricks laid in a spiral herringbone pattern. During his apprenticeship, Leonardo da Vinci helped construct and then set in place the large copper sphere at the top. William J. Anderson, *The Architecture of the Renaissance in Italy* (London: Batsford, 1909), plate 4. Courtesy of Galvin Library, Illinois Institute of Technology.

the animals, Leonardo sketched a general view of the hoist along with a series of views of its most important details. These multiple-view drawings, done in vivid geometrical perspective, are a signature feature of his notebooks.

Leonardo's career as an independent technician began as an offshoot of an assignment from Lorenzo de' Medici. Lorenzo had directed Leonardo to carry a certain gift to Ludovico Sforza, the new and self-installed ruler of the duchy of Milan. Leonardo transformed this charge into a full-time job as the Sforza court's engineer. It turned out to be a fortunate move for him, and he spent nearly two decades there (1482–99). Milan was twice the size of Florence, and the Sforza family presided over an active and powerful court. In a famous letter to his new patron, Leonardo proclaimed his engineering talents and highlighted their uses in war. "I will make bombards, mortars, and light ordnance of fine and useful forms, out of the common type," he stated. He also had promising designs for "covered chariots, safe and unattackable," "covered ways and ladders and other instruments," a way to "take the water out of trenches," "extremely light, strong bridges," and "many machines most efficient for attacking and defending vessels." After enumerating no fewer than nine classes of weapons ("I can contrive various and endless means of offense and defense"), Leonardo then mentioned civilian engineering. "In time of peace I believe I can give perfect satisfaction and to the equal of any other in architecture and the composition of buildings public and private; and in guiding water from one place to another."[6] Yet even the guiding of water, as we will see, was hardly an innocent task.

Ludovico would be formally recognized as duke of Milan some years later (he had seized power by pushing aside his ten-year-old nephew), and then Leonardo would become known as *ingeniarius ducalis* (duke's engineer). But when Leonardo arrived, in the 1480s, Ludovico's claim to the duchy of Milan was shaky. In an effort to create legitimacy for his own regime, Ludovico planned a huge bronze statue, more than 20 feet in height, to commemorate his deceased father, the former and legitimate ruler of Milan. In his letter to the duke, Leonardo shrewdly offered to "undertake the work of the bronze horse, which shall be an immortal glory and eternal honour to the auspicious memory of the Prince your father and of the illustrious house of Sforza."[7] Leonardo, it seems, knew exactly what was expected of him. From this time forward, Leonardo fashioned a career as a court engineer with a strong military slant. His notebooks from Milan are filled with drawings of crossbows, cannons, attack chariots, mobile bridges, firearms, and horses.

Leonardo's drawings create such a vivid image in the mind that it is not easy to tell when he was illustrating an original invention, copying from a treatise, recording something he saw firsthand, or, as was often the case, simply exercising his fertile imagination. Among Leonardo's "technological dreams"—imaginative projects that were beyond the realm of

technical possibility—are a huge human-powered wheel apparently meant to drive the winding and firing of four oversize crossbows, and an immense wheeled crossbow at least 40 feet in breadth. A seemingly impossible horse-drawn attack chariot with rotating knives might actually have seen the battlefield, for there is a note by Leonardo that the rotating knives "often did no less injury to friends than to enemies." Pirate raids on the seaport of Genoa prompted Ludovico Sforza to direct Leonardo to design means "for attacking and defending vessels." Leonardo envisioned a submarine, a sealed, watertight vessel temporarily kept afloat by air in leather bags. But he put the lid on this invention to prevent (as he put it) "the evil nature of men" from using such a vessel to mount unseen attacks on enemy ships.[8]

Another "technological dream" with obvious military potential was Leonardo's study of human-powered flight. In the mid 1490s, Leonardo attempted to apply his philosophical stance that nature was mechanically uniform and that humans could imitate the natural "equipment" of flying animals. He devised several devices for transforming a human's arm or leg motions into the birdlike flapping of a mechanical wing. Several of these appear absurdly clumsy. In one, the pilot—in midflight—continually rewound springs that mechanically flapped the contraption's wings. In another, an especially stout design, there were heavy shock absorbers to cushion crash landings. At least one of these wonders took off from the roof of the Sforza palace. Leonardo's instructions include the note, "You will try this machine over a lake, and wear a long wineskin around your waist, so that if you should fall you will not drown."[9]

Leonardo also worked on the expensive, high-technology military hardware of the Renaissance: gunpowder weapons. Indeed, because the Sforzas already employed a court architect who oversaw civilian building projects, Leonardo devoted himself more soundly to military projects. In his notebooks, one finds full engagement with gunpowder weapons. There are characteristic exploded-view drawings for wheel-lock assemblies (to ignite the gunpowder charge), a water-driven machine for rolling the bars to be welded into gun barrels, and a magnificent drawing of workers guiding a huge cannon barrel through the midst of a bustling foundry (fig. 1.2). Still, as Bert Hall, the leading expert on Renaissance gunpowder technology, has emphasized, the "military revolution" we often associate with gunpowder weapons was a slowly developing affair, given the prohibitively high cost of gunpowder, the laughable state of firearm accuracy, and the surprising deadliness of crossbows, pikes, and

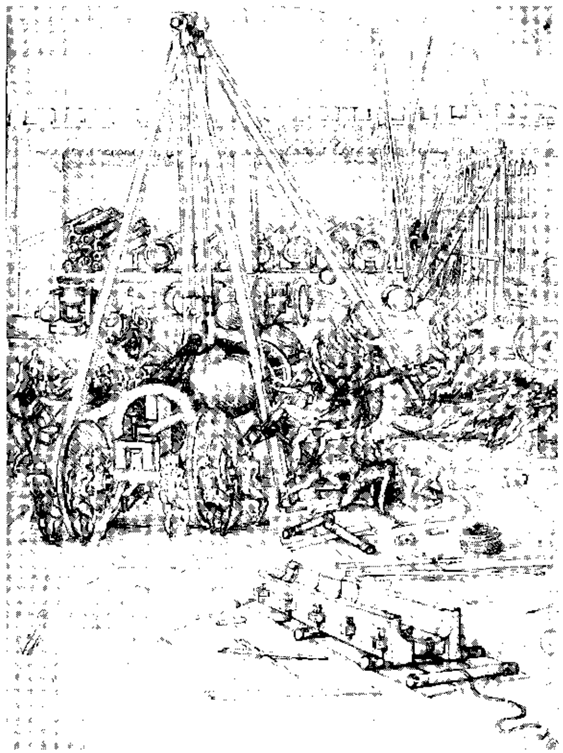

FIG. 1.2. Leonardo and the Military Revolution.

Cannons were the expensive high-tech weapons of the court era. In the late thirteenth century the Chinese invented gunpowder weapons capable of shooting projectiles, and gunpowder cannons were in use by Europeans by the early fourteenth century. In this drawing Leonardo captured the bustle of a busy cannon foundry, using geometrical perspective. The prohibitively high cost of high-nitrate gunpowder, however, constrained the wide use of gunpowder weapons for many decades to come. The Royal Collection, © 2003 Her Majesty Queen Elizabeth II, RL 12647.

battle axes.[10] (A classic turning point, considered in chapter 2, is Maurice of Nassau's integration of firearms into battlefield tactics in the early 1600s.) Leonardo also devised numerous means for building and defending fortifications. He illustrated several devices meant to knock down the ladders that an attacking force might place to scale a fortified wall. While certainly not such exciting subjects as muskets or cannon, the varied means for attacking or defending a fortification were at the core of Renaissance-era warfare.

Beyond the military projects that occupied Leonardo in Milan it was entirely characteristic of the court era that labor-saving or industrial technologies were little on his mind. Fully in tune with his courtly patrons, Leonardo focused much of his technological creativity on dynastic displays and courtly entertainments. For the oversize statue commemorating Sforza's ducal father and legitimizing his own rule in Milan Leonardo built a full-scale clay model of the horse-mounted figure. The story is told that Leonardo would leave "the stupendous Horse of clay" at midday, rush over to where he was painting the *Last Supper* fresco, "pick up a brush and give one or two brushstrokes to one of the figures, and then go elsewhere." The immense mass of bronze set aside for the monument was in time diverted to make cannons.[11]

Sforza also charged Leonardo with creating court culture directly. Leonardo took a prominent role in devising the lavish celebration of the marriage in 1489 between a Sforza son and princess Isabella of Aragon. Marriages between noble families were serious affairs, of course. The marriage celebration offered a prominent occasion for proclaiming and cementing alliances between the two families, and hosts often commissioned allegorical performances that "were at the same time ephemeral court entertainments and serious occasions for political propaganda." Leonardo's contribution to the marriage celebration mingled the heavens and the earth. Traditionally, scholars have understood *Il Paradiso*, created and staged for the Sforza fest, as a human-centered dance spectacle that included "seven boys representing the seven planets" circling a throne and that featured the unveiling of paradise. At the finale, the figure of Apollo descended from on high to present princess Isabella with the spectacle's text. It is often suggested that Leonardo chafed at having to design theatrical costumes, yet scholars have recently found evidence indicating that Leonardo also built moving stage platforms and settings—and perhaps even an articulated mechanical robot for these festivities. An eyewitness account describes the set of planets as a mechanical model built by Leonardo. Leonardo's notebooks have designs for at least two other moving-set theatricals, one featuring the mechanical elevation of an allegorical "star" while another offered a glimpse of hell complete with devils, furies, and colored fires. The mechanisms would have been complex spring- or cable-powered devices, constructed mostly of wood. Leonardo's much celebrated "automobile" was most likely also for courtly entertainments. These theatrical and courtly "automata" represented a culturally appropriate expression of Leonardo's interest in self-acting mechanisms.[12]

His fascination with self-acting mechanisms is also evident in Leonardo's many sketches of textile machines found in the surroundings of Milan. These automata have led some breathless admirers to call him the "prophet of automation," yet it seems more likely that he was simply recording the interesting technical devices that he saw in his travels. (This is certainly the case in his drawings of Milan's canal system.) Quite possibly he was sketching possible solutions to problems he had spotted or heard about. One of these drawings that we can certainly identify as Leonardo's own creation (ca. 1493–95) was a rotary machine to make sequins, used for ornamenting fine gowns or theatrical costumes. Again, Leonardo expressed his mechanical talents in culturally resonant ways, just as inventors in later eras would focus on self-acting mechanisms for industry and not for courts.

Leonardo's comfortable life with the Sforza court ended in 1499 when France invaded the region and ousted Sforza. "The duke lost his state, his property, and his freedom, and none of his works was completed for him," recounted Leonardo. In the chaotic eight years that followed, Leonardo acted essentially as a mercenary military engineer. He traveled widely, with the application of military technologies never far from his mind, and worked all sides of the conflicts that were rending Italy at the time. (Even while working for the duke of Milan and in the process of designing a warm-water bath for the duchess, Leonardo recorded in his notebooks "a way of flooding the castle" complete with drawings.) In Venice, which was reeling under attack by the Ottoman Turks, he suggested improvements to that city's all-important water defenses; while several years later, armed with the special knowledge gained in Venice, he would advise the ruler of Milan on how to flood Venice. In Florence once again during 1500–1501 he failed to gain any technical commissions (the city had its own engineers) and so he devoted himself to painting and the study of mathematics.[13]

In the summer of 1502 the infamous Cesare Borgia tapped Leonardo to be military engineer for his campaign in central Italy. It is impossible to make a simple reckoning of the shifting alliances that shaped Leonardo's career during these tumultuous years. The Sforza family had originally gained control of Milan with the support of the Florentine Medici. The French invasion of Milan, which cost Leonardo his job at the Sforza court, was aided by Alexander VI (1492–1503), the so-called Borgia pope, none other than Cesare Borgia's father, who in effect traded Milan to the French in exchange for their backing of his rule as pope and their support for his son's military venture. We can be certain that while accompanying Cesare Borgia's wide-ranging military campaign Leonardo witnessed the sack of Urbino, where the Montefeltro family had collected a famous library and an illustrious court (of which more below). In addition to its political consequences, the Borgia campaign furnished the occasion when Leonardo first met Machiavelli and when Machiavelli found his "model" prince in Cesare Borgia, the Duke of Valentino.

Returning to war-torn Florence in 1503 Leonardo gained from that city two commissions characteristic of the era. With the Medici family temporarily exiled, the struggling republican government used the fine arts and public works to help secure its political legitimacy. The city kept a squad of historians busy chronicling its glories. "Florence is of such a nature that a more distinguished or splendid city cannot be found on the entire earth," gushed one such account. In the same celebratory vein, the republic commissioned Leonardo to paint a fresco commemorating the Florentines' victory over Milan in the battle of Anghiari in 1440. The second commission, a giant hydraulic-engineering scheme hatched with Machiavelli's behind-the-scenes assistance, took aim at the enemy town of Pisa. The two men planned to move the Arno River—at once devastating the downstream town of Pisa and improving Florence's access to the sea. Two thousand workers began digging a diversion canal, but when the results were unsatisfactory the scheme was halted. During this unsettled period, Leonardo also served as a consultant on military fortifications for Florence's ally, the lord of Piombino, and on painting and architecture for French-held Milan. Leonardo's continual travels between Florence and Milan brought work on the *Battle of Anghiari* fresco to a crawl. Perhaps even Leonardo experienced some discord when simultaneously working for Milan while memorializing Milan's defeat.[14]

Leonardo's famous anatomical studies began during a lull in the military action. After 1507 Leonardo's notebooks record many detailed sketches of the muscles, bones, and tendons of the human body; his access to the city hospital in Florence made his empirical investigations of high quality. Leonardo also conceived of a series of elaborate analogies between geometry and mechanics, anatomy and geology, and the human body and the cosmos. He also outlined a theoretical treatise on water, but keeping in mind the Leonardo-Machiavelli scheme to destroy Pisa by diverting its river, it is difficult to see this treatise as a "pure" theoretical study.

In French-held Milan once again from 1508 to 1513, Leonardo gained the patronage of Louis XII, king of France, who occasionally directed Leonardo toward a specific technical project but mostly provided him general patronage, giving him ample time for theoretical investigations. Yet Leonardo's second Milan period ended when the Sforza family *recaptured* the city and drove out his newly acquired French patron. Leonardo escaped to Florence, where the Medici family had returned to power, then went on to Rome in the service of Giuliano de' Medici, the brother of Pope Leo X (1513–21). In the next two years Leonardo worked on several specific commissions from Giuliano, who flourished as his brother dispensed patronage his way. While in Rome Leonardo mapped the malaria-ridden marshes around Terracina, on the coast south of Rome, with the aim of draining them, a public health project given to Giuliano by his pope-brother. A Leonardo drawing of a rope-making machine is even stamped with the Medici's diamond-ring symbol. But when Giuliano died in 1516, Leonardo once again found himself without work or patron. At least Leonardo saw the situation plainly, writing, "The Medici made me and ruined me."[15]

Leonardo spent the last three years of his life at the royal court of France. The new French king, François I, gave him the grand title of "the King's foremost painter, engineer and architect." Officially Leonardo was to design a new royal palace and the surrounding canals and waterworks, but these plans were never realized. Instead, Leonardo became in true fashion a distinguished figure at court. The king, wrote one courtier, "was extremely taken with his great virtues, [and] took so much pleasure in hearing him speak, that he was separated from him only for a few days out of the year. [The king] believed that there had never been another man born in the world who knew as much as Leonardo, not so much about sculpture, painting, and architecture, as that he was a very great philosopher."[16]

In addition to his duties as a great philosopher and eminent expert, Leonardo created more courtly entertainments. His friend Francesco Melzi described one automaton that Leonardo built to honor the French king. A lion with a bristling mane, it was led by a hermit. On its entrance, we are told, women in the audience drew back in terror; but when the king touched the lion three times with a magic wand handed to him by the hermit, the lion-automaton broke open and spilled at the king's feet a mound of fleur-de-lys. Such events were famously packed with symbols to test the audience's savvy. Everyone understood the flower as a classic symbol of the French royal house; the lion was a prominent heraldic symbol of a rival court.[17] To the end, Leonardo understood how to adapt his considerable talents to court desires. He died, in France, on 2 May 1519.

THE SPECIAL CHARACTER of technological creativity in the Renaissance, as we have seen, resulted from one central fact: the city-states and courts that employed Leonardo and his fellow engineers were scarcely interested in the technologies of industry or commerce. Their dreams and desires focused the era's technologists on warfare, city building, courtly entertainments, and dynastic displays. A glance at Leonardo's technical notebooks confirms that he was an outstanding engineer, architect, and artist. But a closer examination of them, and the notebooks of his contemporaries, reveals that he was not the solitary genius imagined by some authors. For instance, the Renaissance engineers who sketched Brunelleschi's hoisting machinery for the Florence cathedral include, besides Leonardo, Francesco di Giorgio, Buonaccorso Ghiberti, and Giuliano da Sangallo. And while we have a contemporary's quip that Leonardo "was as lonely as a hangman,"[18] we also know that he met personally with, borrowed ideas from, and likely gave inspiration to a number of fellow court engineers. The intellectual resources and social dynamics of this technological community drew on and helped create Renaissance court culture.

Foremost among these intellectual resources was the distinctive three-dimensionality and depth of Renaissance art and engineering. This owed much to Leon Battista Alberti, renowned as the "father of perspective." Alberti (1404–72) was born into a prominent Florentine merchant-banking family, studied canon and civil law at the University of Bologna, and worked for three decades in the administrative offices of the pope's court. As Anthony Grafton has recently made clear, Alberti was a courtier of courtiers. Even more than Leonardo's, his career was bound up with the court system. In his latter years, to secure a place at the Ferrara court, he wrote what amounted to a how-to manual for succeeding in the court system—with examples conveniently drawn from his own life! He was experienced at the game. His patrons, besides the papal curia, included the princely courts at Ferrara, Rimini, Mantua, and Urbino, as well as the great Florentine builder Giovanni Rucellai. In his astonishing career, he was variously a humanist writer and rhetorician, architectural designer and consultant, literary critic, sculptor, mapmaker, and a leading theorist of painting. "He is the sort of man who easily and quickly becomes better than anyone else at whatever pursuit he undertakes," thought one contemporary.[19] If he had done nothing else, Alberti's learned treatises on architecture and on practical mathematics might prompt latter-day readers to label him an engineer.

Linear perspective, which he turned into his most far-reaching theoretical achievement, was one thing that Alberti did *not* invent. Leading Florentine artists such as Masaccio were already practicing something like linear perspective a decade or more before Alberti's famous treatise *On Painting* (1436). During the same time Brunelleschi, at work on the Florence cathedral, staged dramatic public events that popularized the new technique. Positioned on the steps of the cathedral, Brunelleschi painted small precise "show boxes" of the prominent Baptistry across the square, and dazzled passers-by when they had difficulty telling the difference between his painting of the scene and the real thing. He did the same for the Piazza della Signoria, site of the city's government. Alberti, too, later painted show boxes in which (as he wrote) the viewer could see "huge mountains, vast provinces, the immense round of the sea surrounding them, and regions so distant from the eye that sight was dimmed . . . they were such that expert and layman alike would insist they saw, not painted things, but real ones in nature."[20]

With his treatise on painting, Alberti turned the practice of perspective into a structured theory. In what is now a commonplace of drawing, he directed artists to treat the two-dimensional picture plane on which they worked, whether it was a wall, panel, or canvas, as if it were a window in which a three-dimensional scene appeared. The classic exercise illustrated and popularized by Albrecht Dürer (1471–1528) is to view an object through a nearby pane of glass, or a mirror, that is ruled into squares, and then to transfer what you see, square by square, onto a piece of paper or canvas that is similarly ruled. Dürer's most famous "object," illustrating his 1525 treatise on geometry and perspective and reproduced widely ever since, was a naked woman on her back, suggesting that perspective was not merely about accurately representing the world but about giving the (male) artist power over it. Whatever the object, vertical lines will remain vertical, while receding horizontal lines will converge toward a vanishing point at the drawing's horizon. Parallel horizontal lines, such as on a tiled floor, must be placed at certain decreasing intervals from front to back. Finally, for maximum effect, the viewer's eye must be precisely positioned. In fact, the "show boxes" directed the observers' point

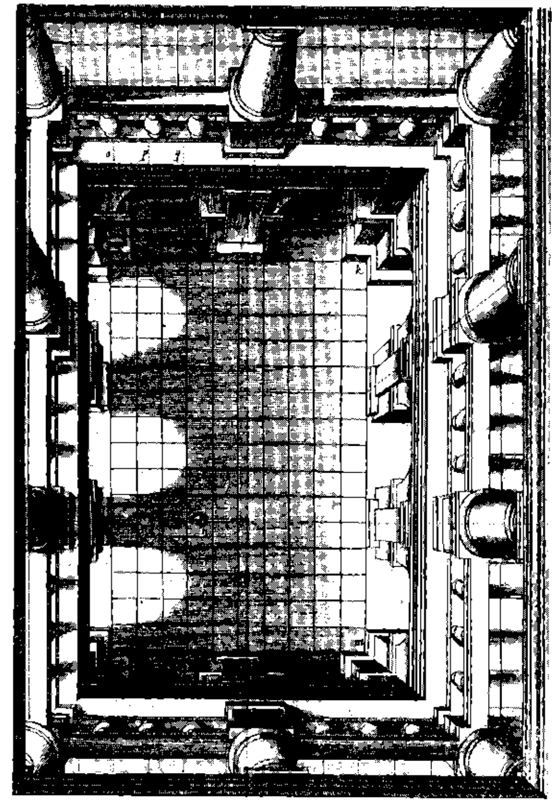

FIG. 1.3. The Gaze of Geometrical Perspective.

Painters, architects, and engineers used geometrical perspective to depict their ideas with precision and persuasion, gaining commissions from the courts and in the process creating culture. Geometrical perspective not merely represented the world but also changed people's ways of thinking. The penetrating eyeball at the symbolic center of this geometrical-perspective drawing hints at the power of the artist's gaze. Joseph Moxon, *Practical Perspective* (London, 1670), plate 36. Courtesy of Illinois Institute of Technology Special Collections.

of view by locating the peephole at the picture's vanishing point, from which they looked at the image reflected in a mirror on the box's far side. Alberti showed how the exact use of perspective can trick the mind's eye into seeing a three-dimensional original.

The geometrical ideas and devices described in Alberti's writings were widely adopted by artists, mathematicians, cartographers, and engineers. And the entertaining show boxes did not harm his flourishing court career. Leonardo, in addition to studying many of Alberti's technical innovations and expanding on his method of empirical investigation, directly incorporated passages of Alberti's writings on painting into his own treatise on the subject.[21] Leonardo even copied many of Alberti's distinctive phrases. It is Alberti's ideas we are reading when Leonardo writes that the perspective picture should look as though it were drawn on a glass through which the objects are seen; or that the *velo*, or square-marked net, locates the correct positions of objects in relation to one another; or that one should judge the accuracy of a picture by its reflection in a mirror. Leonardo even echoed Alberti's dictum that the only "modern" painters were Giotto and Masaccio.

Leonardo's membership in a community of engineers has only recently been appreciated properly. In the absence of an "engineer's guild" listing its members, and because of the pressing needs for military secrecy, we will probably never know all the engineering colleagues with whom Leonardo schemed and dreamed. We do know that chief among Leonardo's contemporaries was Francesco di Giorgio (1439–1501) and that the two men met and in time shared a great deal of technical material. Born in Sienna, Francesco studied painting, sculpture, and architecture. He began his career as a sculptor, then worked as an engineer on his native city's water supply (1469). Francesco became the era's leading military engineer. His career, like Leonardo's and Alberti's, is inseparable from the court system.

Beginning in 1477, Francesco was among the prominent cultural figures that the Montefeltro family welcomed to their fortress-court at Urbino. Court artists there, such as Piero della Francesca, painted the noble family (which numbered one of the Sforza sisters among its members) and authored treatises on painting that were dedicated to the duke and placed in his library. That famous library held some 1,100 richly bound books reportedly costing the whopping sum of 30,000 ducats, about half a year's worth of the payment the Duke of Urbino, a *condottiere* (soldier of fortune) like Sforza, received from his military services. Francesco became the chief designer for the duke's ambitious palace expansion (its scale might be estimated by its stables for 300 horses), and he built a series of military fortresses throughout the state of Urbino. His first treatise on technology—with drawings of such technical devices as artillery, pumps, water-powered saws, methods for attacking fortified walls, catapults, and siege equipment, as well as tips on defending fortifications in an era of gunpowder—was dedicated to the duke (and with its ascribed date of ca. 1475 probably secured his employment by the duke two years later).

Francesco stayed at the Montefeltro court some years after the duke's death, until 1487, when he once again took up work as chief city engineer in Sienna. Also during his post-Urbino years, he traveled frequently to Naples and there advised the Duke of Calabria on military matters. Not by accident, the second edition of the abovementioned treatise on technology was dedicated to this duke while its third edition was illustrated by the duke's court painter. When he was called in to advise on the construction of the cathedrals of Pavia and Milan in 1490, Francesco met Leonardo in person. Francesco had long left the Montefeltro court by the time Leonardo assisted Cesare Borgia with its capture in 1502.

Close study of the two men's notebooks has revealed that Francesco was one source of designs for machines and devices that had previously been attributed to Leonardo alone. For instance, the devices that Francesco described in his treatise on military architecture are in many cases more sophisticated than similar devices in Leonardo's notebooks. We know that Leonardo read and studied Francesco's treatise, since there is a manuscript copy of it clearly annotated in Leonardo's distinctive handwriting. It seems Leonardo simply borrowed from a well-regarded author.

In a curious way, the presence of Leonardo's voluminous notebooks has helped obscure the breadth and depth of the Renaissance technical community, because researchers overzealously attributed all the designs in them to him. At his death in 1519, Leonardo left his notebooks and papers to his "faithful pupil" Francesco Melzi, who kept them at his villa outside Milan for fifty years. Eventually Melzi's son peddled the papers far and wide. Scholars have found caches of Leonardo's papers close to his areas of activities in Milan, Turin, and Paris and as far afield as Windsor Castle, in England. In Madrid a major Leonardo codex was found as recently as 1966. Scholars believe that about one-third (6,000 pages) of Leonardo's original corpus has been recovered; these papers constitute the most detailed documentation we have on Renaissance technology. Unfortunately, only in the last twenty years have scholars abandoned the naïve view that each and every of Leonardo's notebook entries represents the master's original thinking. In his varied career Leonardo traveled widely and often sketched things that caught his attention. His notebooks record at least four distinct types of technical projects: his specific commissions from courtly patrons; his own technological "dreams," or devices that were then impossible to build; his empirical and theoretical studies; and devices he had seen while traveling or had heard about from fellow engineers; as well as "quotations" from earlier authors, including Vitruvius.

Scholars have intensely debated what should count as Leonardo's own authentic inventions. These probably include a flying machine that was a completely impractical mechanical imitation of a bat, some textile machines that remain tantalizing but obscure, and a machine for polishing mirrors. Characteristic of the court culture of Renaissance technology, the textile machine that is most certainly Leonardo's own was the one for making sequins to decorate fancy garments. Leonardo's "inventions" that should be attributed to others include an assault chariot, endless-screw pumps, several lifting apparatuses, and other pump designs that clearly were known in ancient Rome. Leonardo also copied drawings for a perpetual motion machine.

Perhaps the most distinctive aspect of Leonardo's career was his systematic experimentation, evident in his notebooks especially after 1500. He wrote:

> In dealing with a scientific problem, I first arrange several experiments, since my purpose is to determine the problem in accordance with experience, and then to show why the bodies are compelled so to act. That is the method which must be followed in all researches upon the phenomenon of Nature. . . . We must consult experience in the variety of cases and circumstances until we can draw from them a general rule that [is] contained in them. And for what purposes are these general rules good? They lead us to further investigations of Nature and to creations of art. They prevent us from deceiving ourselves or others, by promising results to ourselves which are not to be obtained.[22]

Some objects of Leonardo's systematic investigations were gears, statics, and fluid flow. He made a survey of different types of gears, designing conical and helical gears of wood. He also investigated the causes of crumbling in walls and found that the direction of cracks in walls indicated the source of strain. In studying the resistance of beams under pressure, he arrived at the general principle that for square horizontal beams supported at each end, their resistance varied with the square of their side and inversely with their length—a fair approximation. Fluids were more challenging. To study the flow of water he built small-scale models involving colored water. He also sought general guidelines for placing dams in rivers. Indeed, it may have been with the failed Arno River scheme in mind that Leonardo reminded himself about "promising results to ourselves which are not to be obtained."

The influence of Renaissance engineers on Europe was substantial. The noted medieval historian Lynn White wrote, "Italian engineers scattered over Europe, from Madrid to Moscow and back to Britain, monopolizing the best jobs, erecting wonderful new machines, building palaces and fortifications, and helping to bankrupt every government which hired them. To tax-paying natives they were a plague of locusts, but rulers in the sixteenth century considered them indispensable. Their impact upon the general culture of Europe was as great as that of the contemporary Italian humanists, artists, and musicians."[23]

Gutenberg's Universe

The invention of moveable type for printing led to an information explosion that profoundly altered scholarship, religious practices, and the character of technology. There is much about the printing revolution that conjures up images of enterprising capitalist printers breaking free of tradition-bound institutions. All the same, courts across Europe created large-scale markets for printed works and shaped the patronage networks for writings about technology. The first several generations of printers as well as the best-known early technical authors were, to a surprising extent, dependent on and participants in late-Renaissance court culture.

Printing was a composite invention that combined the elements of moveable metal-type characters, suitable paper, oil-based ink, and a wooden press. Inks and presses were commonly available in Europe, while paper came to Europe by way of China. Paper was being made in China by the third century A.D. from the fibers of silk, bamboo, flax, rice, and wheat straw. Papermaking spread to the Middle East by Chinese papermakers taken prisoner by Arabs in 751. From Samarkand, the great Arabic center of astronomy and learning, the "paper route" passed through Baghdad (793), Cairo (900), Fez (1000), Palermo (1109), Játiva (1150), Fabriano (1276), and Nuremberg (1390). Another route of transmission passed along the coast of Northern Africa, through Spain (beginning of thirteenth century), and into France.

Moveable type was also "first" developed in the Far East, centuries before Gutenberg. Printing from carved stone or wood plates was well advanced in China at the turn of the first millennium; a set of 130 volumes of Chinese classics was printed in 953, and a key Buddhist text was printed using 130,000 plates in 982. The first truly moveable type is credited to Pi Sheng (1041–48), who engraved individual characters in clay, fired them, and then assembled them on a frame for printing. This method was reinvented and improved around 1314 by Wang Cheng, a government magistrate and prolific compiler of agricultural treatises. He commissioned artisans to carve a set of 60,000 specially designed characters and used them to publish up to 100 copies of a monthly gazette. During the Ming Dynasty (1368–1644) moveable wooden characters were used to publish the official court gazette. In Korea characters were first cast from metal (lead and copper) in 1403 and used to print numerous works during that century. The Korean characters spread to China (end of the fifteenth century) and to Japan (1596), and yet metal type did not entirely displace woodblock printing. Traditional woodblock printing persisted, since metal type could not print on two sides of the thin mulberry-tree paper. The further difficulty of moveable type printing in Chinese is evident in Wang Cheng's extraordinarily large set of carved characters.

While it was a vector for the "paper route," the Arab world halted the spread of Asian printing to the West. Islam permitted handwriting the words of Allah on paper but for many years forbad its mechanical printing. The first Arabic-language book printed in Cairo, Egypt, did not appear until 1825.[24]

"The admirable art of typography was invented by the ingenious Johann Gutenberg in 1450 at Mainz," or so stated the son of Gutenberg's partner in 1505. Remarkably enough, the only direct evidence to assess this claim are two legal documents from 1439 and 1455. We know surprisingly little about Gutenberg himself. For almost ten years of his life (1429–34 and 1444–48) not even his city of residence is known with certainty. And while, for instance, tax records tell us that Gutenberg in 1439 had a wine cellar storing 2,000 liters, no one can be sure if he was married to the legendary Ennelin—who may have been his wife, his lover, or a Beguine nun. It is clear that Gutenberg was born into a wealthy and established family of Mainz, sometime around 1400—by printers' fable it was St. John the Baptist's Day, 24 June 1400. His father and several other family members were well connected with the church mint at Mainz, and from them, it seems, Johann gained his knowledge of metal casting, punch-cutting, and goldsmithing.

In 1434 Gutenberg moved to Strasbourg, near the Rhine River in northeast France, and by 1436 he was engaged in experiments on printing. During his residence in Strasbourg he also practiced and taught goldsmithing, gem cutting, and mirror making. In 1438 he agreed to convey "the adventure and art" of printing to two of his mirror-making associates; in effect they paid Gutenberg 250 guilders to create a five-year partnership. However, one of the two died, and his brothers sued Gutenberg in 1439 to be taken into the partnership. The court records indicate little more than that Gutenberg owned a press, had bought lead and other metals, and from them had cast what were called "forms" (a word used to describe the molding or casting of iron). A goldsmith testified that Gutenberg had paid him 100 guilders in 1436 for "that which pertains to the use of a press." Secrecy was an overriding concern of Gutenberg's. When his partner was dying, Gutenberg had all the existing "forms" melted down in his presence. He also directed a helper to take apart an object with "four pieces" held together by two screws, quite likely an adjustable mold for casting type. More than this we will probably never know. To finance these experiments, Gutenberg borrowed large sums of money.[25]

Gutenberg left Strasbourg in 1444, but it is unclear what he did and where he went until his return to his native Mainz four years later. Money surely mattered. Shortly after his reappearance in Mainz, he secured a 150-guilder loan guaranteed by a relative. In 1450 he borrowed 800 guilders from a merchant named Johann Fust, and soon enough an additional 800 guilders with the proviso that Fust was to become a profit-sharing partner in "the works of the books" (namely the printing of the Latin Bible). These "works" comprised perhaps six presses and twenty printers and assistants. In 1455, generating the second court dossier, Fust sued Gutenberg for the repayment of the two loans including interest, a total of over 2,000 guilders. It is often assumed that this court action wiped out Gutenberg's finances and deprived him of his livelihood, but in fact the court required Gutenberg only to repay the first 800 guilders.

Gutenberg retained his half-share in the Bible sales and revenue from other printing jobs, and a recent researcher concludes that he not only repaid Fust but also regained possession of the printing equipment held as collateral. Fust set up a new and highly successful partnership with Peter Schöffer, who had also worked with Gutenberg; between Fust's death in 1466 and his own in 1503, Schöffer published at least 228 books and broadsides. For his part, Gutenberg continued in the printing trade and employed at least two workmen, who became successful printers in their own right after his retirement in 1465. In that year, as the Archbishop of Mainz formally declared, "by special dispensation have we admitted and received him as our servant and courtier." The honor gave Gutenberg a financially secure retirement and, until his death in 1468, the privileges of a nobleman.[26]

Gutenberg's principal inventions were the adjustable mold for casting type and a suitable metal alloy for the type. Understandably, the two lawsuits reveal few technical details of the type-molding apparatus, but a Latin grammar and dictionary printed in Mainz in 1460 (by whom is not clear) points out that its successful printing resulted from the "marvellous consistency in size and proportion between patterns and moulds." We can see why such consistency would be important in type that would be assembled in lines and locked into a frame when placed on the printing press. The letters "M" and "W" are roughly the same width, but "i" and "W" are not. Making different size letters of exactly the same depth and height-on-paper required an adjustable type mold. Gutenberg also struggled to find a type metal that would be easy to melt and mold, yet hard enough to be durable. Again, while the exact composition of Gutenberg's own alloy is not known, the first printed book that describes typecasting, Biringuccio's *Pirotechnia* (1540), of which more later, states, "the letters for printing books are made of a composition of three parts fine tin, an eighth part of lead, and another eighth part of fused marcasite of antimony." Analysis of samples from the printshop of Christopher Plantin from 1580 are 82 percent lead, 9 percent tin, and 6 percent antimony, with a trace of copper.[27]

Printing traveled quickly. By 1471, printing establishments had sprung up in a dozen European cities as far away as Venice, Rome, and Seville. By 1480, there were two dozen printing cities in northern Italy alone, while printers had moved east to Cracow and Budapest and north to London and Oxford. By 1500, there were printers as far north as Stockholm and as far west as Lisbon.

The printing press made a little-known German theology professor named Martin Luther into a best-selling author and helped usher in the Protestant Reformation. The Reformation is officially dated from 31 October 1517, the day Luther tacked his Ninety-Five Theses onto the church door at Wittenberg, Germany. His Theses were written in Latin, not the language of the common people, and church doors had been "the customary place for medieval publicity." Yet, printers sensed a huge market for his work and quickly made bootleg copies in Latin, German, and other vernacular languages to fill it. It was said that Luther's theses were known across Germany in two weeks and across Europe in a month. Luther wrote to Pope Leo X, another Medici pope and brother of Leonardo's onetime patron: "It is a mystery to me how my theses . . . were spread to so many places. They were meant exclusively for our academic circle here." Within three years (1517–20) enterprising printers had sold over 300,000 copies of Luther's writings. "Lutheranism was from the first the child of the printed book, and through this vehicle Luther was able to make exact, standardized and ineradicable impressions on the minds of Europe," writes historian Elizabeth Eisenstein. Eventually, Luther himself hailed printing as "God's highest and extremest act of grace, whereby the business of the Gospel is driven forward."[28]

The Catholic Church responded to the specific theological arguments Luther had raised but could not stop the spread of the printed word. And in this instance, the medium formed the message. The Protestant movement's emphasis on individuals' reading the Bible themselves required a massive printing effort. Whatever their personal beliefs, printers thus had material reasons to support Protestantism. Even the Catholic Church unwittingly helped the cause. Beginning in 1559, the Church issued its notorious *Index of Prohibited Books*, a terror to free-thinking authors and publishers in Catholic countries. But for Protestant-leaning authors it amounted to free publicity, and for printers in Protestant countries it amounted to a conveniently compiled list of potentially best-selling titles.[29] Machiavelli and Galileo were among the well-known figures featured in the *Index*.

It was in part because of the fumbling attempts at repressing printing in the Catholic countries of southern Europe that printing flourished in northern Europe. During the forty years from 1500 to 1540 no fewer than 133 printers produced more than 4,000 books in the Netherlands, whose publishing trade was then centered in the city of Antwerp. Only Paris surpassed Antwerp in population and commercial activity, and it was in Antwerp that Christopher Plantin (c. 1520–89) transformed the craft of printing into an industry. Born in France and apprenticed as a bookbinder in Paris, Plantin moved to Antwerp and by 1550 shows up as "boeckprinter" in that city's guild list. He established his own independent press in 1555. Ten years later, when other leading printers had between two and four presses, Plantin had seven; at the height of his career in 1576 he had a total of twenty-two presses and a substantial workforce of typesetters, printers, and proofreaders.

Although it is tempting to see printers as proto-capitalists—owing to their strong market orientation and substantial capital needs—their livelihood owed much to the patronage and politics of the court system.

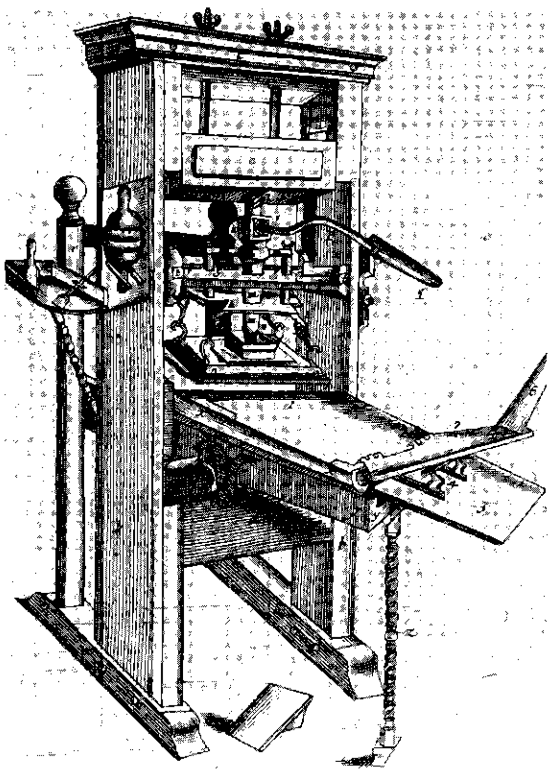

FIG. 1.4. Early Dutch-Style Printing Press.

Christopher Plantin's secret weapon? The pioneering authority on early printing, Joseph Moxon, identified this as a "new fashioned" printing press invented in Amsterdam and widely used in the Low Countries. It is similar to the seventeenth-century printing presses on exhibit today at the Plantin-Moretus Museum (Antwerp). Joseph Moxon, *Mechanick Exercises* (London, 1683), plate 4. Courtesy of Illinois Institute of Technology Special Collections.

Plantin's first book, printed in 1555, was an advice manual for the upbringing of young ladies of the nobility, printed in Italian and French. Plantin benefited from the goodwill and patronage of Cardinal Granvelle and of Gabriel de Zayas, secretary to King Philip II of Spain. With Philip II's patronage, including a healthy direct subsidy, Plantin in the 1560s conceived and printed a massive five-language Bible in eight volumes. During 1571–76, "his period of greatest prosperity," Plantin kept his many

presses busy printing Bibles and liturgical books for the king of Spain. In these years his firm sent to Spain no fewer than 18,370 breviaries, 16,755 missals, 9,120 books of hours, and 3,200 hymnals. Botanical works, maps, dictionaries, and literary and scholarly works of many kinds rounded out his catalogue. "Plantin's firm in Antwerp thus gleaned a lion's share of rewards from the expansion of an overseas book trade in Spain's golden age," writes Eisenstein. "Plantin himself became not only Royal Typographer but chief censor of all his competitors' output while gaining a monopoly of all the liturgical books needed by priests throughout the far-flung Habsburg realms."[30]

When the political winds shifted, Plantin quickly changed his tack. In 1578, when the Spanish were driven from Antwerp temporarily, Plantin became official printer to the new authorities, the States General, and soon printed many anti-Spanish tracts. But when in 1585 the Spanish threatened to take Antwerp again, and this time for good, Plantin opened a second office in Leiden and for two years served as printer to the newly founded University of Leiden. As Eisenstein observes, "Plantin's vast publishing empire, which was the largest in Europe at the time, owed much to his capacity to hedge all bets by winning rich and powerful friends in different regions who belonged to diverse confessions."[31]

Plantin's massive output suggests the huge scale of book production at the time. In the first fifty years of printing (1450s-1500) eight million books were produced in Europe. The economics of the new technology were impressive. For instance, in 1483 a certain Florence printer charged about three times more than a scribe would have for reproducing Plato's *Dialogues*, but the printer made more than a thousand copies while the scribe would have made just one. Moreover, handwritten scribal copies contained idiosyncratic alterations from the original, while the printer's copies were identical to each other, an additional dimension of quality. This economy of scale sharply reduced the cost of books, which meant that one scholar could have at hand multiple copies from several scholarly traditions, inviting comparison and evaluation. Eisenstein writes, "Not only was confidence in old theories weakened, but an enriched reading matter also encouraged the development of new intellectual combinations and permutations."[32] In this way, the availability of vastly more and radically cheaper information led to fundamental changes in scholarship and learning. Printing lent a permanent and cumulative character to the fifteenth-century Renaissance. The same was true for many other technologies.

Technology and Tradition

We tend to think of technology as cumulative and irreversible, permanent and for all time, but it has not always been so. Technologies have ebbed and flowed with the cultures that they were intrinsically a part of. The Middle Ages became known as the "dark ages" because Western Europeans had "lost" contact with the classical civilizations of Greece and Rome (whose knowledge of science, medicine, and technology resided in the libraries of the Islamic world). Not until the incremental technical changes of the late Middle Ages were combined with the innovation of three-dimensional perspective, courtesy of Alberti, Leonardo, and others, and with the possibility of exact reproduction through printing did technology become a cumulative and permanent cultural element. This cultural shift, which we understand to be characteristic of the "modern" world, deserves to be better understood.

Transfer of technology before the Renaissance could be hit-or-miss. Machines invented in one time, or place, might well need to be rediscovered or even reinvented. Indeed, something very much like this occurred after the great technological advances of Song China (960–1279). The list of technologies invented in China during these years is formidable indeed, including not only paper and printing, but also gunpowder weapons, magnetic compasses, all manner of canals, locks, and hydraulic engineering, as well as the industrial-scale production and consumption of iron. China's ironmasters in the northern Heibei and Henan regions were using coke to smelt iron ore fully five centuries before the English industrial revolution. Chinese silk-reeling mills, farm implements (made of iron), and bridges are among the numerous other advanced technical fields where, as historian Arnold Pacey writes, "techniques in use in eleventh-century China . . . had no parallel in Europe until around 1700."[33]

Yet these pioneering Chinese technologies were not reliably recorded with the rigorous geometrical perspective that allowed Renaissance engineers to set down their ideas about the crucial workings of machines. Chinese drawings of silk-reeling mills, for example, are often so distorted that to Western eyes, accustomed to geometrical perspective, it is very difficult to tell how they should be built. The definitive *Science and Civilisation in China* series offers numerous instances of inaccurate and/or incomplete illustrations of textile machines. In the volume on textile spinning, it is clear that hand scrolls (themselves works of fine art) invariably have the "best" illustrations of textile technology while the post-Song-era encyclopedias and technical books are plagued by incomplete and misleading illustrations. In fact, the progressive corruption of images of silk-reeling machinery in successive encyclopedia editions of 1313, 1530, and 1774 rather clinches the point. In the wake of political disruptions after 1279 Song China's technical brilliance was lost not only to the Chinese themselves but also to the West, whose residents formed an inaccurate and incomplete view of China's accomplishments.[34]

Eugene Ferguson, a leading engineer-historian, has brilliantly shown how quickly technical drawings might be corrupted, even in the West. He compares a series of drawings made by Francesco di Giorgio around 1470 with copies made in the 1540s by artist-scribes in Sienna who had been specially trained to copy mechanical drawings.[35] The results are startling. Francesco's original perspective drawings of hoisting cranes and automobiles are workable, if not always brilliantly designed. But the scribes' copies are something else; many mechanical details are missing or distorted. For instance, a hoisting crane's block-and-tackle system, useful for gaining mechanical advantage in lifting, was reduced in the copy to a single pulley, which provides no mechanical advantage. Similarly, Francesco's original versions of a bar spreader and bar puller resembled modern turnbuckles in that the *right*-handed threads on one side of a square nut and the *left*-handed threads on the other served to push apart or pull together the *ends*. In the copyist's version, however, left-handed threads are shown throughout, creating a device that would simply move the *nut* toward one end or the other. While Francesco's originals rigorously observe the conventions of three-dimensional perspective (so that parallel lines running right-to-left are really parallel while lines running back-to-front converge to a vanishing point at the rear of the drawing), the copyists' versions often have no vanishing point.

For some of these devices, a knowledgeable technical worker might have been able to "see through" the warped perspective of the copied drawing and "fix" the errors. But now imagine that the copyist's version was again copied by hand and that additional distortions were introduced in the process. In time, recreating Francesco's original devices would become hopelessly difficult. His designs, like those of the Chinese technologists, would effectively be "lost." The point is that before the combination of printing and geometrical perspective, inventions made in one generation might not be available to successive generations or for that matter beyond the close circle of colleagues sharing notebooks or craft practices. In these circumstances, a disruption to the social order, like the fall of a ruler and destruction of his library, would entail a disruption in the technological tradition. Technological change could not be permanent and cumulative.

In these terms a permanent and cumulative tradition in technology, enabled by the invention of printing and perspective, appeared first in central Europe's mining industry. Vannoccio Biringuccio's *Pirotechnia* (1540), Georgius Agricola's *De re metallica* (1556), and Lazarus Ercker's *Treatise on Ores and Assaying* (1580) are brilliantly illustrated printed books that even today convey the details of distant technologies. These three volumes have several striking similarities, including once again surprisingly close connections to late-Renaissance court culture, even though these authors came from diverse social backgrounds. Biringuccio was a supervisor of silver and iron mines with extensive practical experience, Agricola was a university-trained humanist, and Ercker was an upwardly mobile mining supervisor who married into a prominent family. As Pamela Long has shown in her studies of early-modern technical writing, each author was associated with the mining industry of central Europe at a time when technology-won efficiencies were urgently needed. Costs were rising because an earlier mining boom (of 1460 to 1530) had already tapped the obvious veins of silver, gold, and copper, while prices were falling due to the influx of Spanish gold and silver stripped from the New World. Thus, wealthy investors and the holders of royal mining rights eagerly consumed information about mining technology that promised substantial economic returns. As Long writes, "the great majority of 16th-century mining books were written by Germans in the regions of the empire where the capitalist transformations of mining were most pronounced—the Harz Mountains near Goslar, the Erzgebirge Mountains in Saxony and Bohemia, and the Tyrolian Alps to the south."[36] Biringuccio, an Italian, had visited mines in this region and wrote to urge his countrymen to make comparable investments in technological changes in their own copper mines.

Each of these three authors flourished by gaining the courtly favor of "prince-practitioners," as Long calls them, who had a special interest in mining and metal technology. Biringuccio (1480–1539) worked for Italian princes, including the Farnese of Parma and Alphonso I d'Este of Ferrara, for the ruling Petrucci family of his native Sienna, and for the Florentine and Venetian republics; and at the time of his death was director of the papal foundry and munitions plant in Rome. Agricola (1494–1555) was born in Saxony during a great expansion of that region's silver mines, graduated from Leipzig University, studied medicine in Italy, and served as town physician in the Erzgebirge region. He turned his close observations of mining and careful investments to his personal enrichment (by 1542 he was among the twelve wealthiest inhabitants of Chemnitz, Saxony) and to courtly recognition by the Saxon prince Maurice, who gave him a house and land in 1543 and three years later made him burgomaster and later councilor in the court of Saxony. His famous *De re metallica* is dedicated to the Saxon princes Augustus and Maurice.

The same Saxon princes figured in the career of Lazarus Ercker (ca. 1530–94). After attending the University of Wittenberg and marrying into a prominent family, he was named assayer at Dresden by the elector Augustus. Within a year, he dedicated a practical metallurgical handbook to Augustus, who named him general assay master for Freiberg, Annaberg, and Schneeberg. Then, Ercker aligned himself with a new prince-practitioner, Prince Henry of Braunschweig, who named him assay warden of the Goslar mint. After dedicating his second book, on minting, to Henry's son, Julius, duke of Braunschweig-Wolfenbüttel, Ercker was named master of the Goslar mint. Moving to Bohemia in the mid-1560s, Ercker was made control assayer in Kutná Hora (Kuttenberg) through the influence of his second wife's brother. His wife Susanne served alongside Ercker as "manager-mistress" of the mint for many years. His *Treatise on Ores and Assaying*, first published in 1574, was dedicated to the Emperor Maximilian II, from whom he received a courtly position. Ercker was named chief inspector of mines by Maximilian's successor, Rudolf II, who also gave him a knighthood in 1586.[37]

Each of these three authors praised the values of complete disclosure, precise description, and openness often associated with the "scientific revolution." These books detailed the processes of mining, smelting, refining, founding, and assaying. Biringuccio and Agricola used extensive illustrations to convey the best technical practices of their time (see fig. 1.5). Biringuccio's *Pirotechnia* features 85 wood-block engravings while Agricola's *De re metallica* has more than 250. Agricola hired illustrators to make detailed drawings of "veins, tools, vessels, sluices, machines, and furnaces . . . lest descriptions which are conveyed by words should either not be understood by the men of our times or should cause difficulty to posterity."[38]

Even the less practical illustrated volumes known as "theaters of machines" published by Jacques Besson (1578) and Agostino Ramelli (1588) reflected the support of aristocratic and royal patrons. These books were

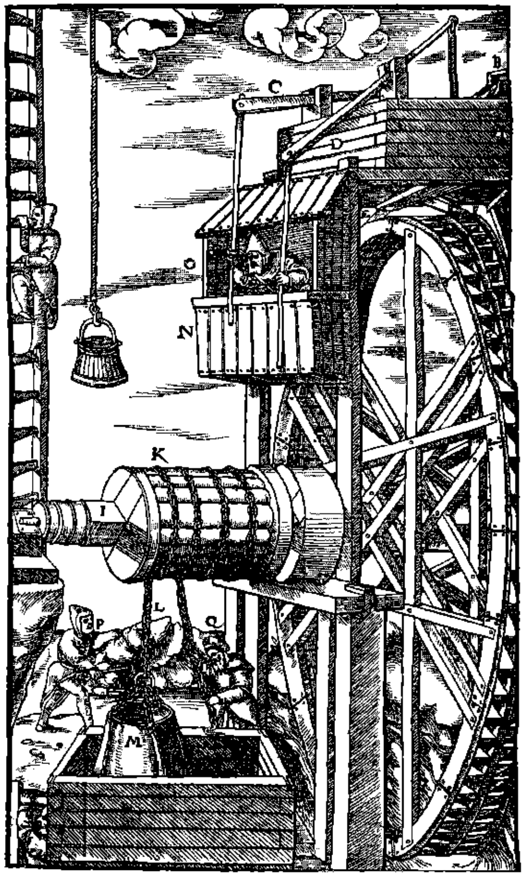

FIG. 1.5. Agricola's Lifting Crane.

Agricola hired illustrators to make detailed drawings, like this vivid illustration of a two-directional lifting crane powered by 36-foot-high waterwheel, "lest descriptions . . . conveyed by words . . . not be understood." Georg Agricola, *De re metallica* (1556; reprint, Berlin: VDI Verlag, 1928), 170. Courtesy of Illinois Institute of Technology Special Collections.

something like published versions of Leonardo's technological dreams, in that they recorded often highly imaginative designs that no one had built. Besson was engineer at the court of France's King Charles IX. Ramelli, an Italian military engineer, was also in the service of the king of France when his book—*Diverse and Ingenious Machines*—was published. While Besson's book had 60 engraved plates, Ramelli's book featured 195 full-

page copperplate engravings of grain mills, sawmills, cranes, water-raising machines, military bridges, and catapults. Ramelli devised more than 100 different types of water-raising machines. Eugene Ferguson observes that Ramelli "was answering questions that had never been asked and solving problems that nobody . . . [had] posed. There is no suggestion that economic forces induced these inventions. The machines were clearly ends, not means." Yet many of Ramelli's machines, including a sliding vane water pump that is original to him, were eventually realized, as the problems of friction and materials were overcome. Ferguson concludes, "The seeds of the explosive expansion of technology in the West lie in books such as these."[39]

The scientific revolution was also surprisingly dependent on printing technology and courtly patronage networks. Tycho Brahe, a young Danish nobleman who taught himself astronomy through printed books in the 1560s, had access not only to accurate printed versions of all of Ptolemy's work (including a new translation of the *Almagest* from the Greek), but also to tables that had been recomputed on the basis of Copernicus's work, to printed sine tables, trigonometry texts, and star catalogues. Tycho could directly compare star tables computed from Copernicus and Ptolemy. On the island of Hveen, a gift from the Danish king, Tycho's observatory, Uraniborg, had no telescope; but it did have a well-stocked library, fifty assistants, and a busy printing press.

Galileo was not only a first-rate scientist but also a prolific popular author and imaginative scientist-courtier. His career began with a landmark study of mechanics that owed much to his observations of large hoisting machines at the Arsenal of Venice, and he secured his fame with another technological breakthrough—the telescope. Among the astronomical discoveries he reported in *Starry Messenger* (1610), something of a best-seller across Europe, were the four moons of Jupiter. Galileo named them the "Medicean stars" in a frank bid for the favor of Cosimo de Medici, the namesake and latter-day heir of the great Florentine powerbroker. In 1616 the Catholic Church placed Copernicus's work on its *Index* of prohibited works, while Galileo's own *Dialogue on Two World Systems* (1633), which left little doubt about his sympathies for the Copernican system, also made the *Index*. Because of his open support of the sun-centered cosmology, Galileo was placed under house arrest, where he worked on the uncontroversial topic of classical mechanics. Yet even this treatise had to be smuggled out of Italy by a Dutch printer, Louis Elsevier, and printed in Leiden as *Discourses on Two New Sciences* (1638). "I have not been able," wrote Galileo in 1639, "to obtain a single copy of my new dialogue. . . . Yet I know that they circulated through all the northern countries. The copies lost must be those which, as soon as they arrived in Prague were immediately bought by the Jesuit fathers so that not even the Emperor was able to get one."[40]

THE DESIRES AND DREAMS of Renaissance courts and city-states defined the character of the era's technology and much of the character of its culture. Leonardo, Francesco, Alberti, and other engineers of the Renaissance era worked on war making, city building, courtly entertainments, and dynastic displays because that is what courtly patrons valued and that is what they paid for. We can easily broaden our view to include Italy's famous luxury glass and fancy silk industries and the impressive state-directed Arsenal of Venice without significantly changing this basic picture of court dominance. In a major study of the silk industry, Luca Molà writes, "While in the fourteenth and in the first half of the fifteenth century merchant oligarchies ruling over Italian cities dedicated considerable energy to the development of silk manufacturing, later on champions of the new industry were to include the major princely families of the peninsula (such as the Visconti, the Sforza, the Gonzaga, the Este, the Medici, the Savoia, the della Rovere), more than one pope, and the monarchs of Spain, France, and England."[41] Courts in China, Turkey, India, the Persian empire, and Japan also during these years, in varied ways, channeled technologies toward court-relevant ends.[42]

The patrons of Renaissance technologies, especially when compared with those of eras discussed in later chapters, were not much concerned with labor-saving industrial technologies or with profit-spinning commercial ones. Similarly, the early generation of moveable type printing was deeply dependent on European courts for large-scale printing jobs, while authors of the books that made technology into a cumulative and progressive tradition depended on courtly patronage networks. The pervasiveness of the court system in the Renaissance should not really surprise us, since it was the dominant cultural and political actor at the time, fully analogous to the commercial and industrial institutions as well as the nation-states, corporations, and government agencies that followed with different imperatives and visions for technologies.

2

TECHNIQUES OF COMMERCE

1588–1740

THE NOBLE COURTS, city-states, and prince-practitioners who employed Renaissance technologists to build cities, wage war, entertain courts, and display dynasties were not using technologies principally to create wealth or improve industries. Rather, they were using their wealth—from land rents, banking, and mercenary activities—to pay for the creation and deployment of technologies.[1] This practice shaped the character of that era's technology and—through the resulting cathedrals and sculptures, urban palaces and rural villas, court automata and printed books—the character of Renaissance society and culture as well. We have seen how this occurred in the growth and expansion of the mining industry in central Europe around 1600 and in the profusion of court-sponsored technology books on mining.

The imperatives of creating wealth reshaped the content and purpose of technology during the great expansion of commerce across Europe. In Venice, Florence, and other Italian city-states commercial activities began expanding even before the Renaissance, of course, but the commercial era was fully realized a bit later in Antwerp, Amsterdam, and London. Each of these three cities was the node for far-flung trading networks, constructed when commercial traders following up on the pioneering "voyages of discovery" created maritime trading routes to Asia, Africa, and the New World. Even though no single year marks a shift from one era to another, the influence of Renaissance-era courts was on the wane by around 1600 while the influence of commerce was distinctly rising.[2] It is important to emphasize the historical distinctiveness of the commercial era and to avoid reducing it to an "early" but somehow failed version of industrial