26 August 1977, Volume 197, Number 4306

SCIENCE

The Mind's Eye: Nonverbal Thought in Technology

"Thinking with pictures" is an essential strand in the intellectual history of technological development.

Eugene S. Ferguson

This scientific age too readily assumes that whatever knowledge may be incorporated in the artifacts of technology must be derived from science. This assumption is a bit of modern folklore that ignores the many nonscientific decisions, both large and small, made by technologists as they design the world we inhabit. Many objects of daily use have clearly been influenced by science, but their form and function, their dimensions and appearance, were determined by technologists—craftsmen, designers, inventors, and engineers—using nonscientific modes of thought. Carving knives, comfortable chairs, lighting fixtures, and motorcycles are as they are because over the years their designers and makers have established shape, style, and texture.

Many features and qualities of the objects that a technologist thinks about cannot be reduced to unambiguous verbal descriptions; they are dealt with in his mind by a visual, nonverbal process. His mind's eye is a well-developed organ that not only reviews the contents of his visual memory but also forms such new or modified images as his thoughts require. As he thinks about a machine, reasoning his way through successive steps in a dynamic process, he can turn it over in his mind. The designer and the inventor, who bring elements together in new combinations, are each able to assemble and manipulate in their minds devices that as yet do not exist.

If we are to understand the development of Western technology, we must appreciate this important, if unnoticed, mode of thought. It has been nonverbal thinking, by and large, that has fixed the outlines and filled in the details of our material surroundings for, in their innumerable choices and decisions, technologists have determined the kind of world we live in, in a physical sense. Pyramids, cathedrals, and rockets exist not because of geometry, theory of structures, or thermodynamics, but because they were first a picture—literally a vision—in the minds of those who built them (*1*).

This article attempts to clarify the nature and significance of nonverbal thought. It traces the development of nonverbal thought as practiced by technologists since the Renaissance, points to the many drawings and pictures that have both recorded and stimulated technological developments, and reviews the graphic inventions, such as pictorial perspective, that have lent system and clarity to nonverbal thinking. A concluding section considers changing attitudes toward the nonverbal component of technology as they have been reflected in engineering curricula and suggests some effects of such changes upon the nature of our technology.

The author is professor of history at the University of Delaware and curator of technology of the Hagley Museum, Greenville, Delaware 19807.

The Nature of Design

There may well be only one acceptable arrangement or configuration of a complex technological device, such as a motorcycle, but that arrangement is neither self-evident nor scientifically predictable. The early designers of motorcycles could not ask science to tell them where to put engine, battery, fuel tank, and spark coil; they had to make their choices on other grounds (see cover). In time, wrong choices would be revealed, but not by scientific analysis. Making wrong choices is the same kind of game as making right choices; there is often no a priori reason to do one thing rather than another, particularly if neither had been done before. No bell rings when the optimum design comes to mind. Nor has the plight of designers changed fundamentally in the 20th century. They must still weigh the imponderable and sound the unfathomable. All of our technology has a significant intellectual component that is both nonscientific and nonliterary.

The creative shaping process of a technologist's mind can be seen in nearly every man-made object that exists. The sweep of a suspension bridge, for example, is much more than an exercise in geometry. The distinctive features of three great suspension bridges in New York—the Brooklyn, George Washington, and Verazzano Narrows—reflect more strongly the conceptualization of their designers and the times of their construction than they do the physical requirements of their respective sites. Different builders of large power boilers use many common elements in their designs, but certain characteristics of internal "style" distinguish the boilers of one maker from those of another. The opportunities for a designer to impress his particular way of nonverbal thinking upon a machine or a structure are literally innumerable. This open-ended process can be seen in the design of a familiar, compact machine such as a diesel engine.

The designer of a diesel engine is a technologist who must continually use his intuitive sense of rightness and fitness. What will be the shape of the combustion chamber? Can I use square cor-

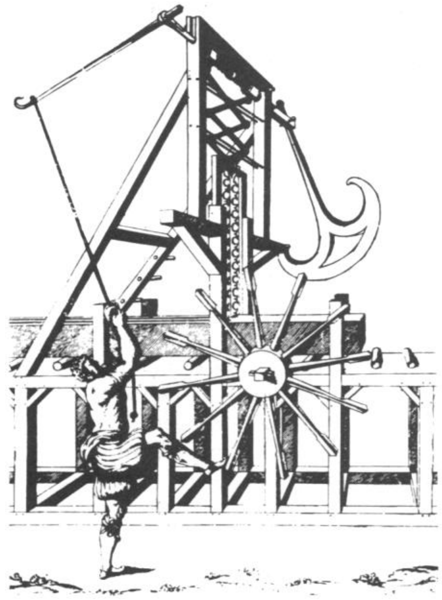


Fig. 1. J. Besson's sawmill, 1578. The saw blade is moved vertically by lazy tongs, actuated by right- and left-handed screw threads on rod at top of frame. The pendulum at right stores energy between strokes of saw (9). [Courtesy of the Hagley Museum]

ners to gain volume, or must I use a fillet to gain strength? Where shall I place the valves? Should it have a long or short piston? Such questions have a range of answers that are supplied by experience, by physical requirements, by limitations of available space, and not least by a sense of form. As the designer draws lines on paper, he translates a picture held in his mind into a drawing that will produce a similar picture in another mind and will eventually become a three-dimensional engine in metal. Some decisions, such as wall thickness, pin diameter, and passage area may depend upon scientific calculations, but the non-scientific component of design remains primary. It rests largely on the nonverbal thought and nonverbal reasoning of the designer, who thinks with pictures.

Renaissance Picture Books

Beginning with the Renaissance of the 15th century, a vast body of technical knowledge has been recorded and conveyed in the form of drawings and pictures. As soon as printed books superseded manuscript codices, large numbers of identical illustrations began to be reproduced. The circle of technologists whose minds could be engaged by a particular problem or stimulated by a particular idea was thus indefinitely enlarged. Two traditions of illustrated technical works, extending from the time of the Renaissance, can be identified. The first originated in engineers' notebooks and was carried on in printed works such as the heavily illustrated machine books of Agostino Ramelli (1588) and Jacob Leupold (1724–1739). This tradition has been disruptive and progressive, as it has suggested new and novel ideas about machines to anyone who can interpret the illustrations. The origins of the explosive expansion of technology in the West lie in books such as these. Manuals of technical processes, such as Georg Agricola's classic book of 1556 on mining and metallurgical processes, comprise the second tradition, which diffused established techniques but did not promote radical change.

The first tradition was well established by the end of the 15th century, when Leonardo da Vinci was busy filling thousands of pages of his private notebooks with technical drawings. A number of other extensive and elaborate manuscript codices of technical drawings were already in existence; they were being studied, copied, and circulated among the community of engineers, many of whom were compiling their own illustrated notebooks. The appearance in many of the notebooks of whole series of similar drawings, copied from each other or from other sources, attests to the active exchange of information in pictorial form among technologists (2). Some of the authors, remembered as artists as well as engineers or architects, have been identified; many remain anonymous.

One of the most influential of the manuscript notebooks, and one which demonstrates in microcosm how technical information has been transmitted through drawings, was Book Seven of Francesco di Giorgio Martini's *Trattato di Architettura*, composed around 1475. It was never published, but several surviving manuscript copies suggest its wide circulation. One of the copies, incidentally, includes marginal comments in the hand of Leonardo da Vinci (3).

Francesco's codex was one of the many heavily illustrated technical works of the 15th and 16th centuries that conveyed their messages chiefly through drawings. An explanatory text generally accompanied each of Francesco's drawings, but the text was complementary to the drawing and had no meaning in its absence. Some engineers' notebooks contained no text at all. For example, one codex (4), handed down in an old Urbino family, displays many drawings quite similar to Francesco's, but no words were thought necessary to elucidate the drawings. Francesco di Giorgio also designed a series of 72 marble reliefs in the ducal palace in Urbino. Most of the plaques were conventionally stylized groups of arms and armor, but a few bore recognizable details of water pumps, sawmills, cranes, and a variety of military siege machinery (5, 6). On these plaques Francesco depicted objects that other technologists might ponder and improve upon.

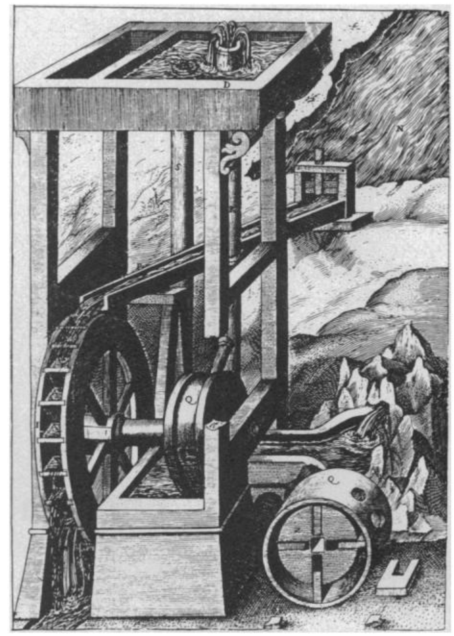


Fig. 2. A. Ramelli's rotary positive-displacement pump, 1588 (10). First appearance of this now widely used device. Note the two discharge ports in casing (at right), the lower to provide maximum flow, the upper to clear the wedge of fluid remaining after vane covers lower port. Rotor turns counterclockwise. [Courtesy of the Hagley Museum]

Francesco's importance in the history of technological thought is established by the clear influence of his drawings on his distant successors. The machine books of Vittorio Zonca (1607) and Jacob de Strada (two volumes, 1617–1618), published more than a hundred years after Francesco's death in 1501, contain a number of his drawings, obviously copied directly from his 15th-century manuscript codices (7, 8). Francesco's intellectual successors included Jacques Besson and Agostino Ramelli, whose machine books were published in 1569 and 1588, respectively. These books displayed many unconventional, often radically novel, devices and mechanisms (9, 10) (Figs. 1 and 2). Overly complex assemblies of gears, cams, and links, so easy for us to dismiss as mere fantasy, became imbedded in inventive minds through repeated exposure to these machine books and their progeny.

By the time of Ramelli's book, in 1588,

there was a body of technological inventions that far exceeded society's demands or needs. As one pages through the hundred varieties of water-lifting machines in Ramelli's book, the conviction grows that Ramelli was answering questions that had never been asked, solving problems that nobody but he, or perhaps another technologist, would have posed. There is no suggestion that economic forces induced these inventions. The machines were clearly ends not means. Nevertheless, nearly every one of Ramelli's mechanisms, however elaborate or extravagant, has been put to some use in succeeding centuries. He and his colleagues, supported in their imaginative excursions by royal and aristocratic patrons, were in fact happily compiling pictorial catalogs of material progress.

In the early 18th century, Jacob Leupold, a German instrument maker, published a monumental series of machine books entitled *Theatrum Machinarum*. Published between 1724 and 1739, the work collected and distilled in ten volumes, including nearly 500 plates, the mechanical repertoire of machine books accumulated over nearly 200 years. Even the drawing styles of his predecessors were preserved in Leupold's plates.

Leupold's books and many others of the 17th and 18th centuries were pored over in the early 19th century by French technical pedagogues at the École Polytechnique, and their drawings, in uncounted copies and copies of copies, were incorporated into the charts of "mechanical movements" that gained wide popularity in the 19th century (Fig. 3). Recognizable elements of Francesco's drawings can be found in books published in Italy, France, England, and the United States from the 17th through the 20th century (Figs. 4–7) (*11–14*).

The second tradition of transmitting technical information through illustrations was established in the mid-16th century with books by Biringuccio and Agricola on the winning and working of metals and other minerals (*15, 16*). Both were books of solid technical information, of current best practice as described by their knowledgeable authors. Both books used many words to describe the various processes of assaying, mining, smelting, refining, founding, yet both were heavily illustrated. Biringuccio's *Pirotechnia* (1540) included about 85 simple but informative wood engravings; Agricola's *De Re Metallica* (1556) was illustrated by over 250 wood engravings, many quite elaborate. More than 50 illustrations were full-page plates (Fig. 8). Agricola, in the preface of his book, remarked on the difficulty of explaining machines and other technical matters fully and clearly. He wrote, ". . . with regard to veins, tools, vessels, sluices, machines, and furnaces, I have not only described them, but have also hired illustrators to delineate their forms, lest descriptions which are conveyed by words should either not be understood by men of our own times, or should cause difficulty to posterity."

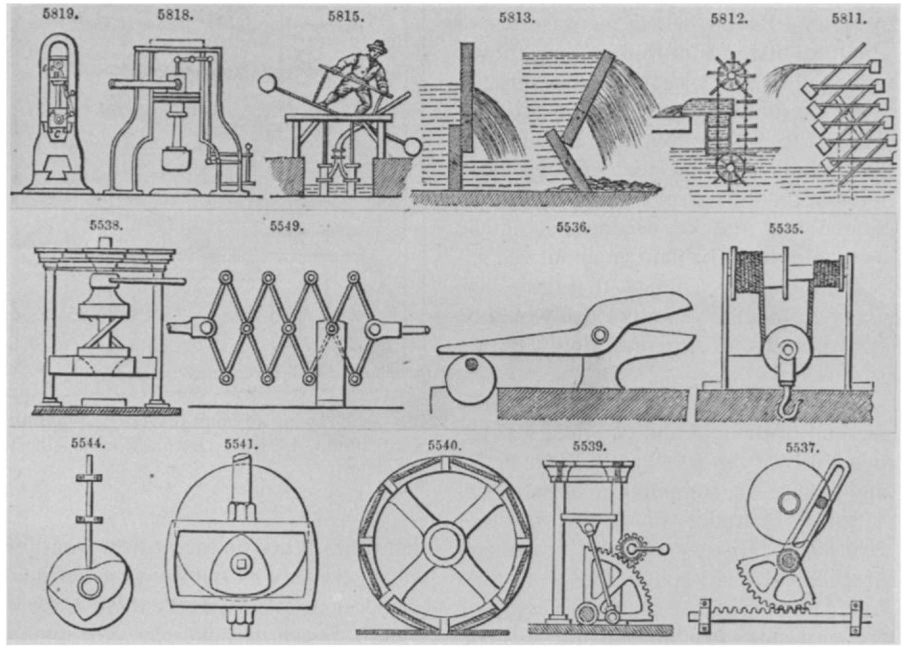


Fig. 3. Typical chart of mechanisms (*13*). [Courtesy of the Smithsonian Institution]

The tradition of describing machines, tools, and processes in words supported by clarifying illustrations culminated in two French works of the 18th century: Diderot's *Encyclopédie* (1751–1780) and the Académie des Sciences' *Descriptions des Arts et Métiers* (1761–1788), which are described below in the context of Baconian science. It may be said that, although the books of this tradition preserved a remarkable record of tools and processes, their influence as agents of progressive change was much less than that of the Francesco di Giorgio–Ramelli tradition.

The Illiberal Arts

Other intellectual currents of the 16th and 17th centuries encouraged the visual, nonverbal study of machines. A few humanists foresaw an end to learning, as disputations on ancient texts loaded the mind with wordy formulas that had little substance. In 1531, Juan Luis Vives, a philosopher and tutor in the English court, urged scholars to pay attention to the world around them, including the work of artisans, in order that their speculations might be grounded in reality rather than in "foolish dreams." Two years later, in his work on Gargantua, François Rabelais portrayed teacher and pupil visiting the shops of goldsmiths, watchmakers, printers, and the like in order to study the work of artisans and thus complete what the author conceived to be a liberal education (*17*, pp. 5–7).

Bernard Palissy, the noted French potter, also attacked the narrow learning of scholars in *Discours admirables* (1580). He invited them to come to his workshop, where, he claimed, in only 2 hours they might see for themselves that "the theories of many philosophers, even the most ancient and famous ones, are erroneous in many points" (*17*, pp. 1–2). In 1669, Isaac Newton advised a young friend who was traveling to the Continent to seek out and observe their "Trades & Arts wherein they excell or come short of us in England," as well as to see what the Dutch had achieved in the grinding and polishing of "glasses plane." Military installations should be inspected, he added, as should mines and metal works; perhaps his friend could also learn whether pendulum clocks might be used for finding longitude. An appreciable part of Newton's letter was concerned with gaining first-hand acquaintance with technological matters (*18*).

By Newton's time, the European intellectual community had been deeply influenced by Francis Bacon's grand scheme to enhance the power and greatness of man through a new and practical science. As part of his comprehensive program, Bacon called for a series of "natural histories of trades," which was intended to study each craft in turn, to describe tools, techniques, and processes, and to make public the technical information that had for so long been known only in workshops. Bacon assumed that the knowledge thus made available would be thought about and improved upon by scholars, that the general level of technical knowledge would be raised, and that progress would be the sure result.

In the decade after 1650, an enormous amount of thought and planning was expended by John Evelyn, William Petty, and others on compiling a massive description of trades, or, in the words of Evelyn, a "History of Arts Illiberal and Mechanical." Although the work was never published, the planners very soon recognized the need for illustrations to illuminate the proposed text. Petty concluded that "bare words being not sufficient, all instruments and tools must be pictured, and colours added, when the descriptions cannot be made intelligible without them" (*19*).

Implicit in this project was the Baconian faith that the systematic study of any art by liberal minds would lead to its improvement. It was supposed that new and useful ideas were bound to emerge when ingenious practices in the various trades were studied and compared. The new ideas, in Bacon's words, would come about "by a connexion and transferring of the observations of one Arte, to the use of another, when the experiences of several misteries shall fall under the consideration of one mans minde" (*20*). Thomas Sprat, a fellow of the Royal Society of London, which was founded in 1662, thought that the histories of trade would encourage the invention of improvements by members of the Society. "A large and an unbounded Mind is likely," he wrote, "to be the Author of greater Productions, than the calm, obscure, and fetter'd Endeavours of the Mechanics themselves" (*21*).

Contrary to Sprat's expectations, members of the Royal Society found other subjects more congenial than the details of workshops, and soon the histories of trade were quietly laid aside.

In Paris, Bacon's program of histories of trades was placed on the agenda of the Académie des Sciences almost as soon as the Académie was formed in 1666. Colbert was actively promoting the project on "Descriptions des arts et métiers" by 1675, but the first chapter was not written until nearly a generation later, in 1704, and nothing was published at that time. Work on the project went forward very slowly, but it was never quite abandoned. When, in the 1740's, Denis Diderot began to make plans for his *Encyclopédie*, he found that some 150 drawings and engravings had been prepared for the now moribund "Descriptions" project. Diderot drew heavily on this earlier work but added much of his own. Eventually, he published nearly 3000 full-page plates in his *Encyclopédie*, perhaps half pertaining directly to and clarifying the written descriptions of crafts and trades (*22*).

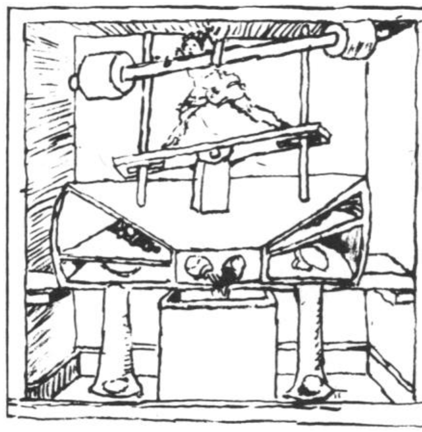


Fig. 4. Drawing of man-driven two-cylinder water pump, 1475 (*3*). [Permission of Alberto Vigevani]

In 1757, after several volumes of the *Encyclopédie* had been published, the Académie's series of descriptions of arts and manufactures was revived by Duhamel du Monceau. Between 1761 and 1788, a handsome folio series of some 80 parts was published under the title *Descriptions des Arts et Métiers* (*23, 24*).

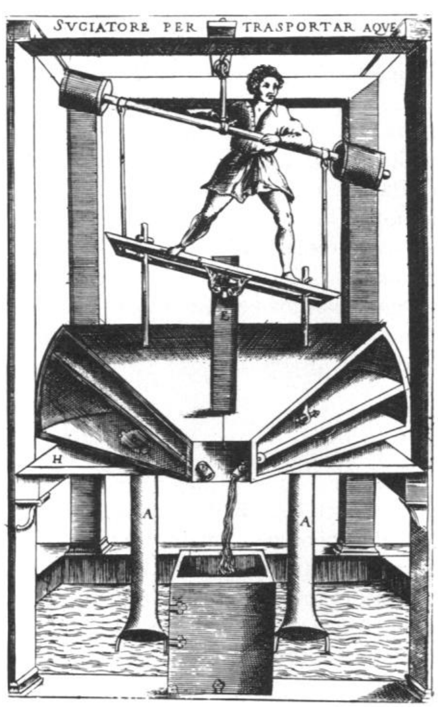


Fig. 5. Engraving of man-driven two-cylinder water pump, 1607 (*7*). [Courtesy of the Hagley Museum]

Diderot's objectives were Baconian, based as they were on the earlier thought and work of the Académie des Sciences. He expected to produce an illustrated series on arts and crafts "that would induce Artists to read, Philosophers to think usefully, and men of power to make effective use of their authority" (*25*).

The French illustrations of workshops and tools (Fig. 9) are important to historians for the record they provide of 18th-century industry, but their significance in stimulating technological change is rather slight. The whole French enterprise was considerably removed from the cutting edge of technological innovation. The *Encyclopédie*, in the tradition of Biringuccio and Agricola, supplied a detailed manual for those who wished to learn how to make something or carry out an industrial process, but the roots of radical change in technology are to be found in books following the tradition of Francesco di Giorgio, Ramelli, Leupold, and in the charts of mechanical movements growing out of that tradition.

Graphic Inventions

More important to Renaissance engineers than scientific knowledge were the inventions in graphic arts that lent system and order to the materials of nonverbal thought. The printed book itself marked a turning point in Western civilization. In the 50 years after the first printed book appeared around 1450, some 8 or 10 million copies of nearly 40,000 different books were printed—an average of two new books a day for 50 years, each issued in an edition of 200 or 250 copies (*26*). Considering the fact that the techniques of printing were new in 1450, the explosive expansion of the art suggests its intellectual impact. Copperplate engravings, very numerous by the latter part of the 16th century, permitted finely detailed technical drawings to be reproduced in large numbers. Woodcuts, while less versatile than copperplate engravings, were nonetheless able to multiply the work of a draftsman by thousands of copies. Thus the quantity of information available to the nonverbal thinker was vastly augmented within a couple of generations.

Nearly as important as the art of printing itself were the techniques of pictorial perspective, which produced a qualitative change in the ease with which the visual image in one mind could be conveyed to another mind (*27*). Since their invention in the 15th century, perspective drawings have provided a consistent and uniform convention for pictorial representation of three-dimensional objects that can be interpreted almost without effort by a viewer. The ambiguity of object size and location in space shown in earlier drawings was swept away by the Renaissance invention of perspective (compare Figs. 2 and 10).

The crucial importance of printing, woodcuts, copperplate engravings, and pictorial perspective cannot be overstressed (*28*). It is difficult to imagine how our Western technological civilization could have grown as it has in the absence of printing techniques that provided multiple identical copies and of pictorial perspective that fixed the rules for realistic pictures readily understandable by craftsman and scholar alike.

Later graphic inventions have clarified or simplified pictorial representation. The "exploded" view, an invention of Leonardo da Vinci, helps to explain reality in a rigorous yet imaginative way. A comparison of drawings by Leonardo (Fig. 11) and Agricola (Fig. 8) shows vividly the advantage of the exploded view over an alternative display of disassembled parts. Orthographic projection, universally used in mechanical drawing since the early 19th century, was clearly used in Albrecht Dürer's book on the geometry of drawing, published in 1525 (*29*, pp. 42–43 and 128–129). An orthographic drawing was easier to make and could convey more information in three views than a perspective drawing, but it was much more difficult to understand. The isometric view, a modification of pictorial perspective suitable for drawings with a limited depth of field, such as machine elements and subassemblies, was introduced early in the 19th century by William Farish, a Cambridge don (*29*, chapter 11). The ordinary graph, or curve, which also appeared in the 19th century, is an invention that converts a mathematical relationship into a visual image. Variations of quantities, plotted along two coordinates, are displayed by a curve connecting the intersections of the two sets of quantities. Characteristic curves that describe performance of machines or materials provide a simple visual image to relate changing variables. If the efficiency of an engine is at issue, for example, an engineer's thoughts turn instinctively to a typical performance curve, that of efficiency versus load; a structural engineer carries a family of stress versus strain curves in his head; even the abstractedly thinking electronics engineer is likely to visualize curves of wave forms.

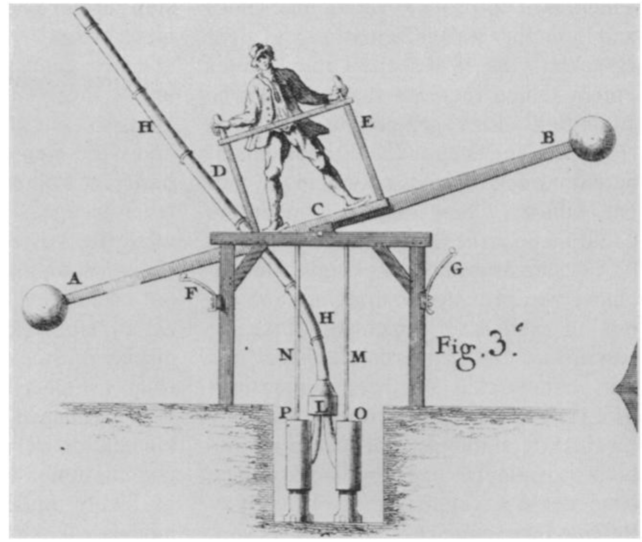
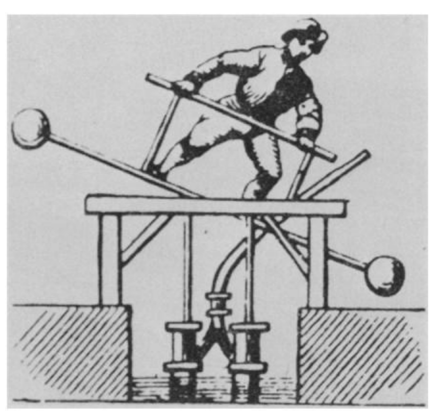


Fig. 6. Water pump, 1739 (*12*). [Courtesy of the Hagley Museum]

In building medieval cathedrals and castles, master workmen frequently employed models to plan and lay out complex portions of the structures. Models were particularly helpful in determining the order of assembly of elements of masonry in vaults as well as in working out the truss arrangements in large roofs. Hugh Herland, master carpenter to Richard II, for example, used numerous models in designing the roof of Westminster Hall (*30*). In 1585, when Pope Sixtus V decided to move the Vatican obelisk, a monolith nearly 100 feet high and 330 tons in weight, to its present location in front of St. Peter's, he appointed a commission to review the several hundred proposals put forward by contenders for the job. Significantly, the successful contender, Domenico Fontana, explained with the help of an elaborate model the way in which he intended to lift and move the unwieldy monolith. His 2-foot model obelisk was made of lead, and the timbers and rigging, including ropes and pulleys, were proportioned accordingly (*31*).

Models of machines submitted in the 17th and 18th centuries for the stamp of approval of the Académie des Sciences were displayed for many years in the Académie's chambers (*32*). In London, the Royal Society of Arts displayed in a public gallery the models that were entered in the society's periodic contests for the best solution to a particular technical problem. The aim of the Society's



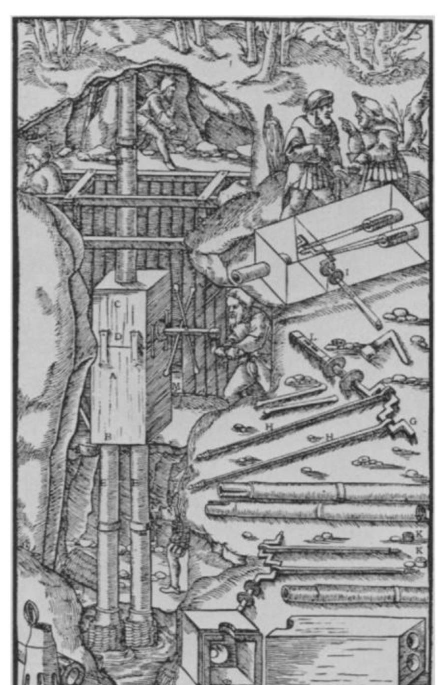


Fig. 7 (left). Water pump, 1943 (*14*). [Courtesy of the Hagley Museum] Fig. 8 (right). Agricola's method of depicting details of two-cylinder water pump, 1556 (*16*). Compare this to Leonardo's exploded view (Fig. 12). [Courtesy of the Hagley Museum] gallery was to provide young mechanics and inventors with information and ideas (33). Until the 1870's, the United States Patent Office required that a model be submitted with every patent application (Fig. 12). The accumulated thousands of patent models were displayed in the Patent Office, where aspiring inventors could inspect them at will (34).

A systematic aid to thinking about machines was provided in drawings and operating models of kinematic linkages, anticipated by Leonardo da Vinci and first constructed in three dimensions by Christopher Polhem, an 18th-century Swedish technologist. Leonardo's notebooks displayed disembodied machine elements in a way that none of the other Renaissance engineers' notebooks did. He showed several variations of pistons, cranks, connecting rods, ball bearings, and roller chain links in order that he might study the elements in isolation, unencumbered by the machines of which they were parts (35). Early in the 18th century, Polhem took Leonardo's idea a step further and constructed in three dimensions a "mechanical alphabet" of machine elements. Just as the writer of words must know the letters, said Polhem, so must the designer of machines know the elements that are available to him. To Polhem, the "five powers"—lever, wedge, screw, pulley, and winch—were the vowels, while the rest of the elements were the consonants. About 20 out of perhaps 80 of Polhem's mechanical alphabet models survive and are on display in Stockholm's Tekniska Museet (Fig. 13) (36). Franz Reuleaux, who in 1875 published the modern doctrine of kinematics of machines, designed and commissioned the building of many sets of nicely finished cast-iron and steel models of kinematic "pairs," which were used as teaching aids in engineering schools (37). About 40 years ago, engineering schools in the United States displayed elaborate panels of gears, cams, and mechanical linkages, all designed to be set in motion simultaneously by a small electric motor (Fig. 14).

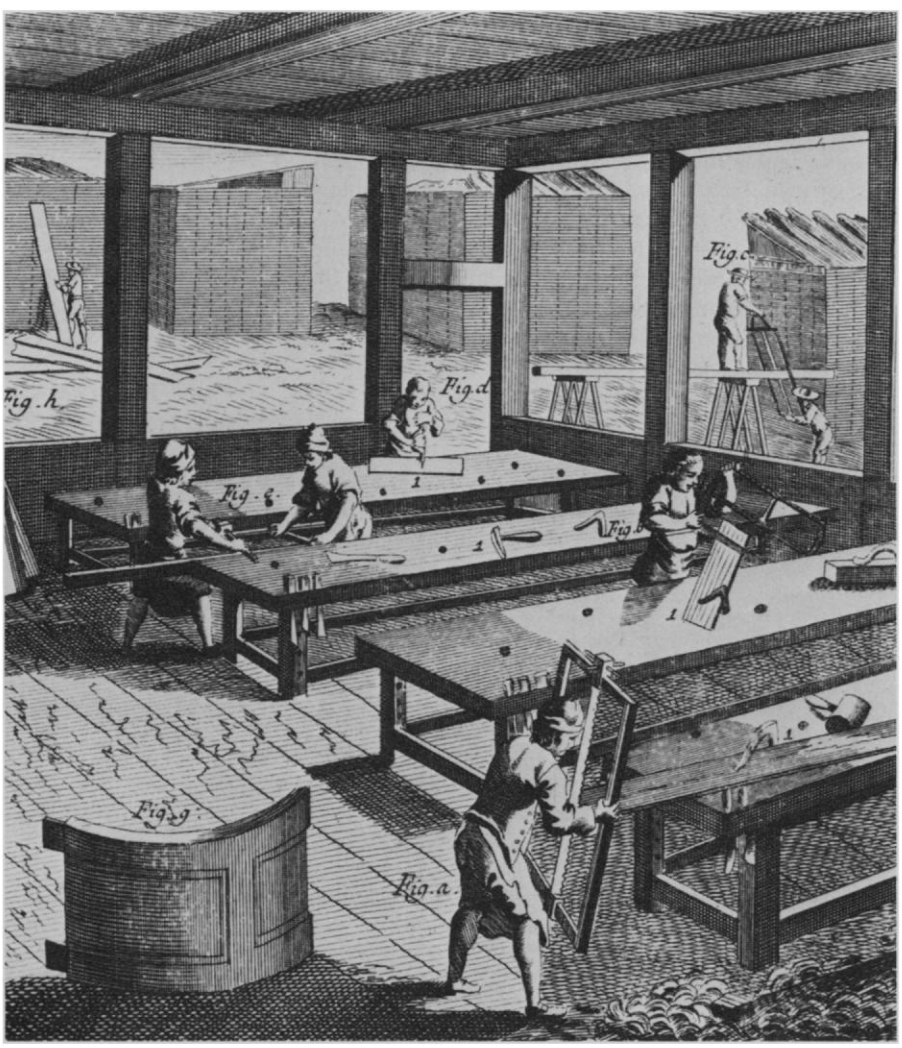


Fig. 9. Joiner's shop (23, vol. 7). Details of joiners' tools were shown in subsequent plates. [Courtesy of the Hagley Museum]

Object Teaching

The utility of visual images in elementary schooling was recognized in the 17th century by Joannes Comenius, whose little picture book, *Orbis Sensualium Pictus* (1658), matched objects to words and introduced the idea of object teaching (38). If a word were associated with an object or a picture, Comenius reasoned, it would be more readily learned and better understood. Although he surely realized that abstract concepts, such as fortitude and prudence, are more difficult than material objects to associate with pictures, he assumed that most minds think with pictures as well as words.

In the 19th century, an enthusiastic group of American educators combined the approaches of Comenius and Johann Pestalozzi, the Swiss educational reformer, in a movement that gained many adherents in the United States (39). In February 1862, for example, observers from New York schools converged upon Oswego, New York, to attend a demonstration of object teaching. Norman A. Calkins, author of the school book *Object Lessons* (published in 1861), hoped that this might be the day when "the philosophy of Bacon, the principles of Comenius, the system of Pestalozzi, and the most practical methods of Object Teaching shall be thoroughly incorporated into the system of instruction in all the schools of our country" (40).

Needless to say, the principles of object teaching have not been universally adopted. Beyond kindergarten, as Rudolph Arnheim has pointed out, "the senses lose educational status," and the school child is fitted into the verbal world of school teachers who are generally unaware of the significance of nonverbal components of thought (41).

Even in an engineering school, a course in "visual thinking" is regarded as an aberration rather than as a discipline that should be incorporated into an engineer's repertoire of skills. A problem such as building a container that will keep an egg from breaking when dropped out of a third-story window is labeled "Rube Goldberg," and the course in which it occurs is picked up as news in the *New York Times* (42). Accustomed to maintaining control of his class, an engineering instructor finds it difficult to pose any problem that requires mere nonverbal thought, that does not have a single unique solution, and that cannot be solved in rigorous mathematical steps.

Art and Technology

In Renaissance engineering, art (as opposed to science) was the guiding discipline, and it might be supposed that the symbiotic relationship between technology and art would be noted by the authors of the illustrated books. On the contrary, a number of enthusiastic technologists of the Renaissance insisted that the mechanic arts had been brought to their current perfection by the power of mathematics, universally applied (*6*, p. 47; *43*). Ramelli, for example, devoted eight large folio pages in the preface of his machine book of 1588 to proving that all mechanic arts rest upon mathematics. Yet when we turn to the body of the work, we find no evidence whatever of his use of geometry or arithmetic or any other branch of mathematics or formal mechanics in the designing of his machines. On close study, the drawings do reveal his intimate knowledge of mechanical principles as derived from experience in workshop and field. They exhibit also a restless originality that is manifested not only in totally new devices, such as Ramelli's rotary pump (Fig. 3), but also in numerous detailed variations of common elements that appear again and again, such as fastenings and shaft bearings. The thoughts expressed in his many drawings of machines were clearly nonverbal. Despite his discourse on the "excellence" of mathematics and its universal utility, Ramelli's intellectual resources were not derived from the science of his day (*10*).

The association of technology with science has become so close that it is difficult to realize that the Renaissance engineer, trained as an artist and retaining the artist's habits of nonverbal thought, had significant counterparts as recently as the 19th century. Benjamin Henry Latrobe, a prominent consulting engineer and architect, was an accomplished watercolorist. Robert Fulton of steamboat fame and Samuel Morse, American inventor of the electrical telegraph, were both artists before they turned to careers in technology. Around the time of the 1876 Centennial Exhibition, John Rogers, who was trained in a machine shop, became the "people's sculptor," producing for American homes many thousands of copies of his nostalgic groups of ordinary people (*44*).

The organization of American technology in the first half of the 19th century tended naturally to follow the pattern set by the world of art, although the connection had escaped historians until recognized recently by Brooke Hindle. American societies for the promotion of the mechanic arts were influenced heavily by the London Society of Arts, which was concerned with both fine arts and the mechanic arts. The Franklin Institute, organized in 1824, awarded prizes at its annual exhibitions and sponsored classes in mechanical and architectural drawing. The American Institute of the City of New York held annual industrial fairs and, like the London Society of Arts, maintained a permanent exhibition of machines and models for the observation and study of mechanics and inventors (*45*).

Visual Thinking

In 1880, when Francis Galton, founder of the science of eugenics, was interviewing scientists in his study of the human intellect, he was astonished to find that most scientists' thought processes were quite different from his own. Galton thought in visual images, he said, while the majority of scientists reported that they thought in words, with seldom any suggestion of an image. In deference to his subjects, most of whom were of "very high repute," he was willing to as-

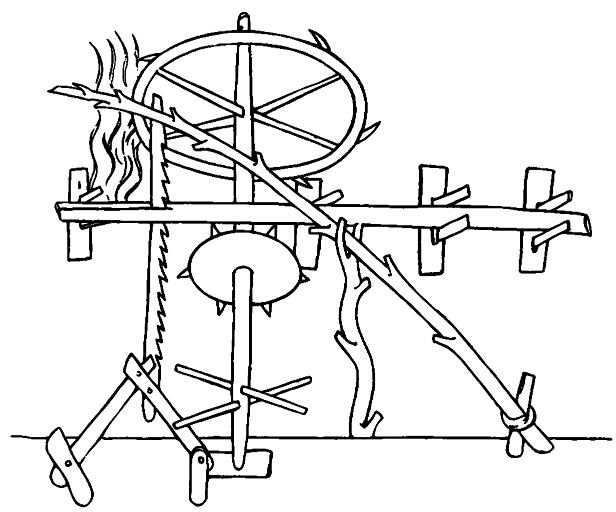


Fig. 10. Up-and-down sawmill of the 13th century. Note confusion of arrangement due to absence of pictorial perspective (*63*). [Courtesy of the Smithsonian Institution]

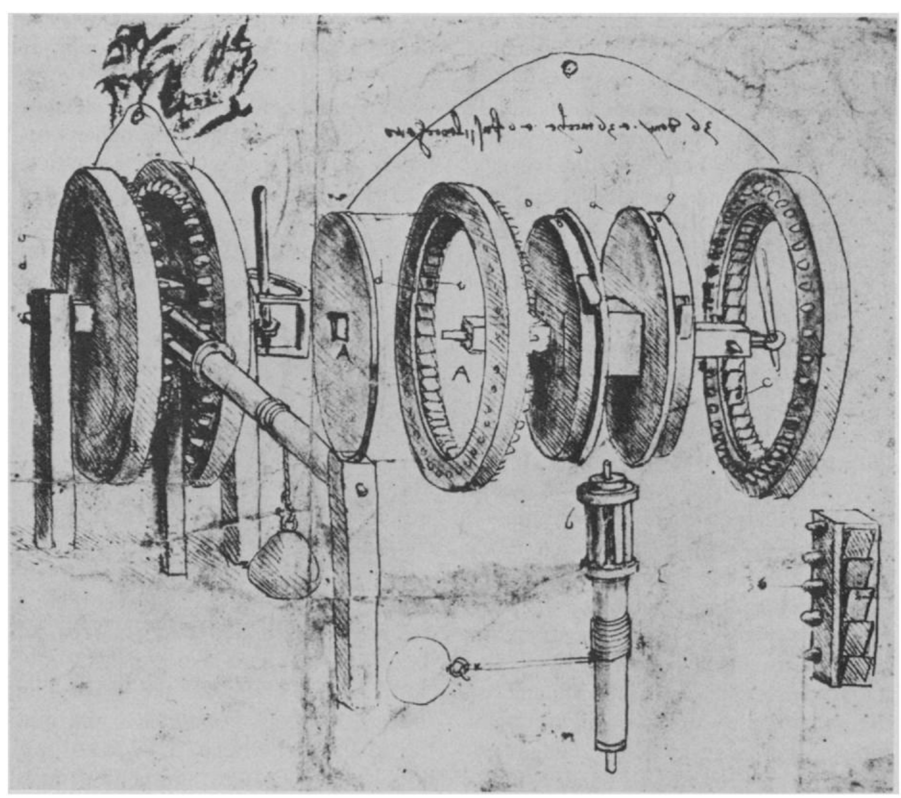


Fig. 11. Assembly (left) and exploded view of weight-driven ratchet device, by Leonardo da Vinci, about 1500 (*64*). The rope drum and lantern pinion have been rotated 90° downward in the exploded view. [Courtesy of the University of Delaware Library]

sume that the "visualizing faculty" was probably inferior to "the higher intellectual operations." Although scientists might at one time have had the visualizing faculty, he added, it had probably been lost by disuse in minds that "think hard" (*46, 47*).

In the early years of the 20th century, the American philosopher William James remarked that a favorite topic of discussion among philosophers was "whether thought is possible without language." There was no question in James's mind; he recognized the possibility of visual and even tactile imagery (*48*). Albert Einstein claimed that he rarely thought in words at all. His visual and "muscular" images had to be "laboriously" translated into conventional language and symbols (*49*).

Sir Flinders Petrie, the great British Egyptologist, was reported by Galton to use a mental "sliding rule" for simple addition. In his head he set one scale against another, and with his mind's eye read off the sum (*46*, p. 66).

Pierre Duhem, the French physicist and historian of science, noted the sharp difference in style between French and English scientists. The French were at home with abstract concepts, he declared, but the British were quite unable to cut through a welter of concrete facts and state general principles. British minds required mechanical models to aid their reasoning. Lord Kelvin, for example, thought the test of understanding of a particular subject in physics was "Can we make a mechanical model of it?" Oliver Lodge's book on electromagnetic theory had so many strings, pulleys, gears, and pipes in his explanatory models that Duhem was driven to observe: "We thought we were entering the tranquil and neatly ordered abode of reason, but we find ourselves in a factory" (*50*).

Whatever may be the mode of thought of scientists, it is certain that technologists who make choices and decisions regarding the design of objects employ a species of nonverbal thought. Over the years, a number of prominent technologists have revealed their mode of thought as they explained how they solved technical problems.

Oliver Evans invented the automatic flour mill, in which bucket elevators and screw conveyors were coordinated to eliminate the need for manually lifting or carrying the grain or flour. He first put the system together in his head, explaining later that "I have in my bed viewed the whole operation with much mental anxiety" (*51*).

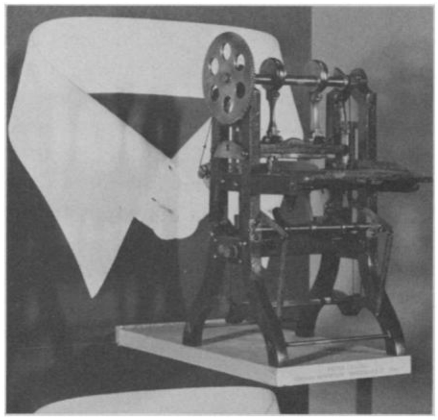


Fig. 12. Patent model of a machine for making paper collars, 1864. The model, about 12 inches high (1 inch = 2.54 cm), was submitted to the U.S. Patent Office by the inventor. [Courtesy of the Hagley Museum]

When James Brindley, engineer of the Duke of Bridgewater's pioneering English canal, was faced with a particularly difficult problem of design, he would go to bed for 1, 2, or 3 days. When he arose he was ready to carry out the designs that existed only in his mind, for he made neither plans nor models (*52*).

In a letter to his partner, Matthew Boulton, James Watt referred to the "straight-line" mechanism, which became his favorite invention, when he wrote, "I have got a glimpse of a method of causing the piston-rod to move up and down perpendicularly, by only fixing it to a piece of iron upon the beam" (*53*).

Marc Isambard Brunel, who designed semiautomatic machines to make ships' pulley blocks in sequential operations, remarked upon the ease with which he expressed his ideas in his drawings; he considered drawing techniques to be the true "*alphabet of the engineer*" (*54*).

Michael Pupin wrote of the imaginative originality of Peter Cooper Hewitt, inventor of the mercury-vapor lamp. "Those who knew him," he recalled, "watching him at work, felt that a part, at least, of Hewitt's thinking apparatus was in his hands" (*55*). Francis Galton, speaking of "inventive mechanicians," observed that "they invent their machines as they walk, and see them in height, breadth, and depth as real objects, and they can also see them in action." How to cultivate the "visualizing faculty" without prejudice to the practice of abstract thought in words or symbols was, to Galton, one of the "many pressing desiderata in the yet unformed science of education" (*46*, pp.78 and 79; *56*).

Scientific Technology

There can be no question about the greatly increased contribution science has made to technology during the 19th and 20th centuries. Borrowing methods as well as information from science, bodies of engineering doctrine have been built up with the ideal of scientific rigor as a guiding principle. Using Edwin Layton's metaphor, the structure of engineering doctrine has become a mirror image of the structure of the physical sciences. The chief difference is in the point of view. The technologist must have a method that "works" and results in real objects, while the scientist wants to understand the nature and details of physical phenomena (*57*).

Yet science, when applied to engineering, is analytical, and in engineering curricula analytical courses have proliferated at the expense of courses attempting to teach design (a very difficult thing to do). Nonverbal thinking, which is a central mechanism in engineering design, involves perceptions, the stock-in-trade of the artist not the scientist. Because perceptive processes are not assumed to entail "hard thinking," it has been customary to consider nonverbal thought among the more primitive stages in the development of cognitive processes and inferior to verbal or mathematical thought (*41, 58*). It is paradoxical that when the National Park Service's Historic American Engineering Record wishes to make drawings of machines and isometric views of industrial processes as part of its historical record of American engineering the only college students who have the requisite abilities attend architectural schools. Engineering schools, accepting a hierarchy of intellectually respectable disciplines, have welcomed each new numerical analytical technique without considering what will be lost when the less numerically rigorous, and therefore less respectable, subjects such as mechanical drawing have been dropped from the curriculum.

Courses in design, which in a strongly analytical engineering curriculum provide one of the few remaining links to the complexities of the real world, may be the next to go, so low is their status among engineering courses (*59*). When they do, we can expect to witness an increasing number of silly but costly errors that occur in advanced engineering systems today. "Metroliner" railroad cars are loaded with sophisticated control gear, but they are unable to run in a snowstorm because a fan sucks snow into the electrical system (*60*). The Bay

Area Rapid Transit is a classic result of systems engineering uninformed by minds that visualize the mundane things that can go wrong in such a system. Absurd random failures that have plagued automatic control systems are not merely trivial aberrations; they are a reflection of the chaos that results when design is assumed to be primarily a problem in mathematics (*61*).

Conclusion

Much of the creative thought of the designers of our technological world is nonverbal, not easily reducible to words; its language is an object or a picture or a visual image in the mind. It is out of this kind of thinking that the clock, printing press, and snowmobile have arisen. Technologists, converting their nonverbal knowledge into objects directly (as when an artisan fashioned an American ax) or into drawings that have enabled others to build what was in their minds, have chosen the shape and many of the qualities of our man-made surroundings. This intellectual component of technology, which is nonliterary and nonscientific, has been generally unnoticed because its origins lie in art and not in science.

As the scientific component of knowledge in technology has increased markedly in the 19th and 20th centuries, the tendency has been to lose sight of the crucial part played by nonverbal knowledge in making the "big" decisions of form, arrangement, and texture that determine the parameters within which a system will operate.

Two results of the abandonment of nonverbal knowledge in engineering colleges can be predicted; indeed, one is already evident. The movement toward a 4-year technician's degree reflects a demand for persons who can deal with the complexities of real machines and materials and who have the nonverbal reasoning ability that used to be common among graduates of engineering colleges. In the longer run, engineers in charge of projects will lose their flexibility of approach to solving problems as they adhere to the doctrine that every problem must be treated as an exercise in numerical systems analysis. The technician, lower in status than the systems engineer, will have the ability but not the authority to make the "big" decisions, while the systems engineer in charge will be unaware that his nonverbal imagination and sense of fitness have been atrophied by the rules of a systematic but intellectually impoverished engineering approach.

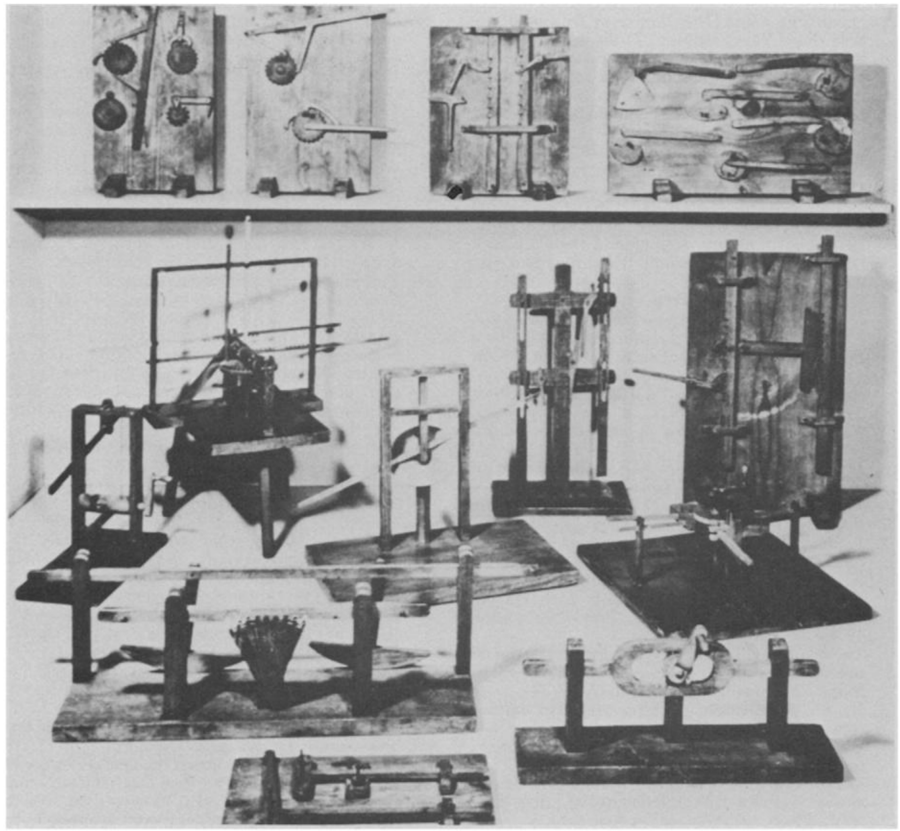


Fig. 13. Christopher Polhem's "mechanical alphabet," 1729. These are surviving models of Polhem's scheme for teaching machine designers the elements available to them. [Courtesy of the Tekniska Museet, Stockholm]

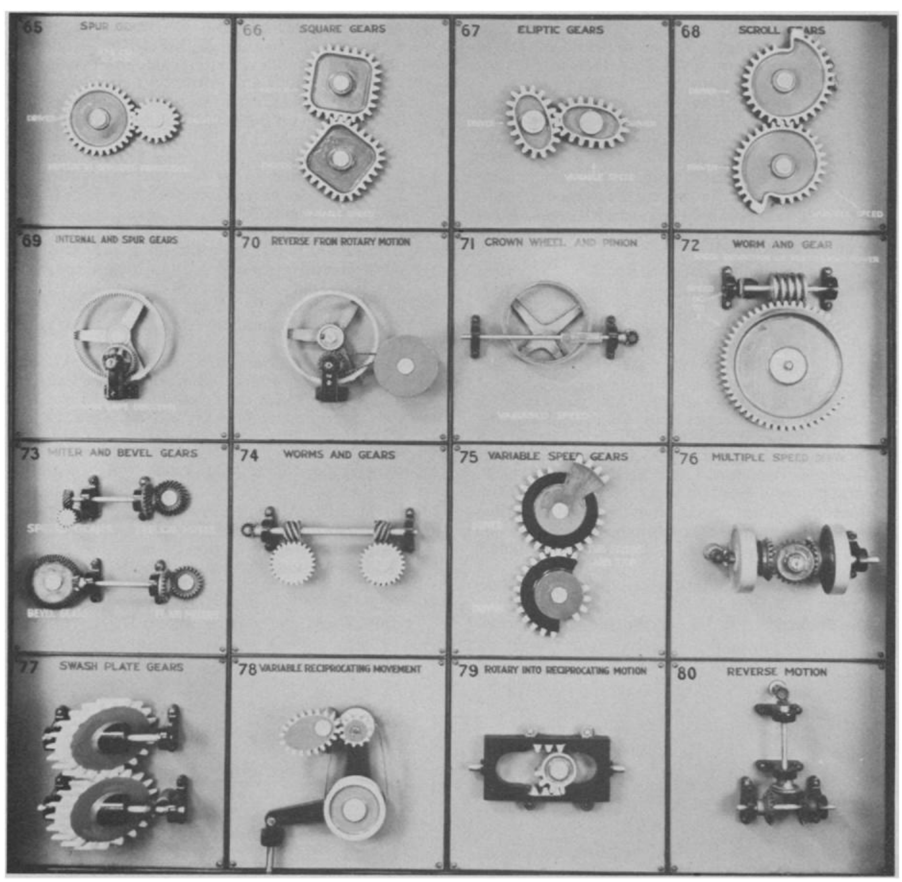


Fig. 14. Panel of kinematic models by W. M. Clark, 1929 (*65*). [Courtesy of the Newark Museum, Newark, New Jersey]

References and Notes

1. David Pye notes [*The Nature of Design* (Reinhold, New York, 1964), p.72] the dependence of theory on empirical design. "If there had been no inventions there would be no theory of mechanics. Invention comes first." In this important book, Pye also (chapter 1) demolishes the notion that form follows function.

G. Scaglia, *Soc. Architect. Hist.* **25**, 90 (1966); B. Gille, *The Renaissance Engineers* (MIT Press, Cambridge, Mass., 1966).

3. L. Reti, *Technol. Cult.* **4**, 287 (1963); for a facsimile edition of the work, see F. di Giorgio Martini, *Trattati di architettura ingegneria e arte militare*, C. Maltese, Ed. (Edizioni Il Polifilo, two volumes, Milan, 1967).
4. Shown me by Frank Prager.
5. F. Bianchini, *Memorie concernenti la città di Urbino dedicate alla sagra real maesta di Giacomo III re della Gran Brettagna & c.* (Rome, 1724).
6. L. White, Jr., in *Developments in the Early Renaissance*, B. A. Levy, Ed. (State Univ. of New York Press, Albany, 1972), p. 41.
7. V. Zonca, *Novo teatro di machine et edificii* (Padua, 1607).
8. J. de Strada, *Künstlicher Abriss allerhand Wasser, Wind-, Ross-, und Hand-mühlen* (Frankfurt, 1617–1618); J. Leupold, *Theatrum Machinarum* (Leipzig, 1724–1730).
9. J. Besson, *Theatre des instrumens mathematiques et mechaniques* (Lyon, 1578).
10. A. Ramelli, *Le diverse et artificiose machine* (Paris, 1588) [M. T. Gnudi and E. S. Ferguson, Transl. (Johns Hopkins U. Press, Baltimore, 1976)].
11. The drawing by Francesco di Giorgio Martini (*3*) of a man-driven two-cylinder water pump will be found only slightly modified in (*7, 12–14*).
12. B. F. de Belidor, *Architecture Hydraulique* (Paris, 1739), vol. 2.
13. E. F. Spon and N. Spon, *Dictionary of Engineering* (London, 1873), figure 5815.
14. W. M. Clark, *A Manual of Mechanical Movements* (Garden City Publishing, Garden City, N.Y., 1943).
15. V. Biringuccio, *De la pirotechnia* (Venice, 1540) [C. S. Smith and M. T. Gnudi, Transl. (American Institute of Mining and Metallurgical Engineers, New York, 1942); paperback edition (MIT Press, Cambridge, Mass., 1966)].
16. G. Agricola, *De re metallica* (Basle, 1556) [H. C. Hoover and L. H. Hoover, Transl., *Mining Magazine*, London, 1912; reprinted, Dover, New York, 1950)].
17. P. Rossi, *Philosophy, Technology and the Arts in the Early Modern Era*, S. Attanasio, Transl. (Harper & Row, New York, 1970).
18. H. W. Turnbull, Eds., *The Correspondence of Isaac Newton, 1661–1675* (published for the Royal Society by University Press, Cambridge, England, 1959), vol. 1, pp. 9–13. For some "useful Hints to Gentlemen that intend to send their Sons Abroad to Travel," stressing the value of observing machinery of all kinds, see *Universal Magazine of Knowledge and Pleasure* (London, 1748), vol. 2, p. 247.
19. W. E. Houghton, Jr., in *Roots of Scientific Thought*, P. P. Weiner and A. Noland, Eds. (Basic Books, New York, 1957), pp. 354–381.
20. F. Bacon, *The Two Books of the Proficience and Advancement of Learning*, London (1605) (Da Capo Press, New York, 1970), book 2, p. 10.
21. T. Sprat, in *History of the Royal Society*, J. I. Cope and H. W. Jones, Eds. (Washington Univ. Press, St. Louis, 1958), p. 392. In the preface of the book of trades by Joseph Moxon [*Mechanical Exercises* (London, 1703), B. Forman and C. F. Montgomery, Eds. (Praeger, New York, 1970)], the editors note, "As is often the case, the initiative of one man—Joseph Moxon—accomplished what a whole variety of well-meaning gentlemen could not."
22. A. M. Wilson, *Diderot* (Oxford Univ. Press, New York, 1972), pp. 242–243.
23. D. Diderot, Ed., *Encyclopédie ou dictionnaire raissoné des sciences, des arts, et des métiers* (Paris, 1751–1780).
24. *Descriptions des arts et métiers, faites ou approuvées par messieurs de l'Académie royale des sciences* (Paris, 1761–1788).
25. J. Assézat, Ed., *Oeuvres complètes de Diderot* (Paris, 1876), vol. 13, p. 370 [S. J. Gendzier, Transl., *Denis Diderot's The Encyclopedia Selections* (Harper & Row, New York, 1969), p. 642].
26. W. T. Berry and H. E. Poole, *Annals of Printing* (Blandford, London, 1966), p. 215.
27. W. M. Ivins, Jr., *On the Rationalization of Sight* (Da Capo Press, New York, 1973), p. 14; see also J. White, *The Birth and Rebirth of Pictorial Space* (Harper & Row, New York, 1958).
28. This point is stressed by S. Y. Edgerton, Jr. [*The Renaissance Rediscovery of Linear Perspective* (Harper & Row, New York, 1975), p. 164]. J. Priestley [*A Familiar Introduction to the Theory and Practice of Perspective* (London, 1870; reprinted, Kraus, New York, 1970)] notes (p. iii) that information "is, in many cases, conveyed with unspeakably more ease and certainty, by the eye, than by the ear."
29. P. J. Booker, *A History of Engineering Drawing* (Chatto & Windus, London, 1963).
30. J. Fitchen, *The Construction of Gothic Cathedrals* (Clarendon, Oxford, 1961), pp. xi, 5, 199, and 302.
31. B. Dibner, *Moving the Obelisks* (Burndy Library, Norwalk, Conn., 1952; reprinted, MIT Press, Cambridge, Mass., 1970), p. 24.
32. R. Hahn, *The Anatomy of a Scientific Institution; The Paris Academy of Sciencex, 1666–1803* (Univ. of California Press, Berkeley, 1971), p. 67; S. A. Bedini, *Technol. Cult.* **6**, 21 (1965).
33. D. Hudson and K. W. Luckhurst, *The Royal Society of Arts 1754–1954* (Murray, London, 1954), pp. 19, 112, and 294–295.
34. A visitor to the U.S. Patent Office [*Am. J. Improvements Useful Arts Mirr. Pat. Off.* **1**, 13 (1828)] told the director that the models "were of incalculable value to the real mechanician" and that as a result of his visit he would be able to "reduce the price of spinning wool, from eight, to one cent per pound." William Thornton, the patent commissioner, averred that the visitor had done so 3 months after his visit. I am indebted to T. Z. Penn for this reference.
35. L. Reti, in *The Unknown Leonardo*, L. Reti, Ed. (McGraw-Hill, New York, 1974), pp. 264–287.
36. For this information I am indebted to Torsten Althin, first director of the Tekniska Museet.
37. A set consisted of about 300 models [A. B. W. Kennedy, *Engineering* **22**, 239 (1876)]. A number of Reuleaux models were located in Cornell University in 1960; I am unsure of their disposition. Reuleaux's idea of a system of models was evidently based on the model collection of his mentor F. Redtenbacher. See F. J. Redtenbacher, *Die Bewegungs-Mechanismen; Darstellung und Erklärung einer Theils der Maschinen-Modell-Sammlung der polytechnischen Schule in Carlsruhe* (Mannheim, 1857).
38. J. A. Comenius, *Orbis Sensualium Pictus* (London, ed. 3, 1672); for a facsimile edition of the work with an introduction by J. Bowen, see (Sydney University, Sydney, 1967).
39. L. F. Anderson, *Pestalozzi* (McGraw-Hill, New York, 1930; reprinted by AMS Press, New York, 1970), p. 61.
40. N. A. Calkin [Barnard's] *Am. J. Ed.* **12**, 633 (1862); W. S. Monroe, *History of the Pestalozzian Movement in the United States* (Syracuse, 1907; reprinted by Arno Press, New York, 1969).
41. R. Arnheim, *Visual Thinking* (Univ. of California Press, Berkeley, 1969), p. 3.
42. S. Blakslee, *New York Times*, 28 November 1975, p. 34.
43. J. Dee, *The Mathematical Preface to the Elements of Geometrie* (1570); for a facsimile of the work with an introduction by A. G. Debus, see (Science History Publications, New York, 1975), p. 13.
44. T. Hamlin, *Benjamin Henry Latrobe* (Oxford Univ. Press, New York, 1955); D. H. Wallace, *John Rogers, The People's Sculptor* (Wesleyan Univ. Press, Middletown, Conn., 1967). It should be noted also that many prominent engineers throughout the 19th century were superb draftsmen.
45. B. Hindle, in *The Pursuit of Knowledge in the Early American Republic*, A. Olesen and S. C. Brown, Eds. (Johns Hopkins Press, Baltimore, 1976), pp. 84–116.
46. F. Galton, *Inquiries into the Human Faculty and Its Development* (Dent, London, ed. 2, 1907), pp. ix, 58, 60, and 78; (Dutton, New York, 1927).
47. For quotations from this work, see A. Roe, *J. Pers.* **19**, 459 (1950–1951).
48. W. James, *The Essential Writings*, B. W. Wilshire, Ed. (Harper & Row, New York, 1971), pp. 68 and 69; Michael Polanyi [*The Tacit Dimension* (Anchor, Garden City, N.Y., 1966)] shows us that we know more than we can tell—that is, we have knowledge that cannot be analyzed or explained. A great deal of Polanyi's "tacit knowing" is used by the technologist in design.
49. O. Holmes, *Schol. Publ.* **6**, 165 (1975); M. Pines, *N.Y. Times Mag.*, 9 September 1973. Einstein's thought processes are considered at length by G. Holton [*Am. Schol.* **45**, 95 (1972)].
50. P. Duhem, *The Aim and Structure of Physical Theory*, P. P. Weiner, Transl. (Atheneum, New York, 1962), pp. 64, 70, and 71.
51. O. Evans, *Oliver Evans to His Counsel, Who are Engaged in Defence of His Patent Rights* (Philadelphia, 1817), pp. 7 and 8.
52. S. Smiles, *Lives of the Engineers: Vermuyden, Myddleton, Petty, James Brindley* (Murray, London, 1904), p. 350.
53. E. S. Ferguson, *U.S. Natl. Mus. Bull.* **228**, 185 (1963).
54. R. Beamish, *Memoir of the Life of Sir Marc Isambard Brunel* (Longman, Green, Longman, and Roberts, London, 1862), p. 321.
55. *Dictionary of American Biography* (Scribner, New York, 1928–36).
56. I have limited my descriptions to the mechanic arts because my own technical nonverbal knowledge is centered upon mechanical engineering. Nevertheless, other technical fields include important segments of nonverbal knowledge. Metallurgists, chemical engineers, and ceramic engineers, to name only three groups of technologists, know more about their materials than they can describe. Cyril Stanley Smith has often noted the significance of nonverbal, "sensually acquired" knowledge in metallurgy [*Ann. Sci.* **34**, 53 (1977)].

E. Layton, Jr., *Technol. Cult.* **12**, 562 (1971); see E. Layton, Jr., *ibid.* **15**, 31 (1974) and O. Mayr and E. Layton, Jr., *ibid.* **17**, 662, 697 (1976).

58. "The arts are neglected," R. Arnheim in (*41*) writes, "because they are based on perception, and perception is disdained because it is not assumed to involve thought." A textual passage sparked this article [A. F. C. Wallace, *Rockdale: the Growth of an American Village in the Early Industrial Revolution, 1825–1865* (Knopf, New York, in press)] and is as follows: "Indeed, it has become conventional to assume that thought itself is merely a kind of internal speech and to disregard almost completely those kinds of cognitive processes which are conducted without language, as thought they were somehow more primitive, and less worthy of intellectual attention."
59. W. R. Lynn, *Science* **195**, 151 (1977).
60. E. C. Burks, *New York Times*, 23 January 1975, p. 15.
61. C. G. Burck, *Fortune* **92**, 104 (July 1975).
62. W. W. Beaumont, *Motor Vehicles and Motors* (Lippincott, Philadelphia, 1900), p. 311.
63. R. Willis, Ed., *Facsimile of the Sketchbook of Wilars de Honecort* (London, 1859), p. 43.
64. L. da Vinci, *Il Codice Atlantice di Leonardo da Vinci* (Florence, 1973), vol. 1.
65. One of the ten panels on display in the Newark Museum.

66. I thank G. Basalla, L. Bryant, D. A. Hounshell, and the late B. R. Leaman for help with the "hard thinking" in this article.