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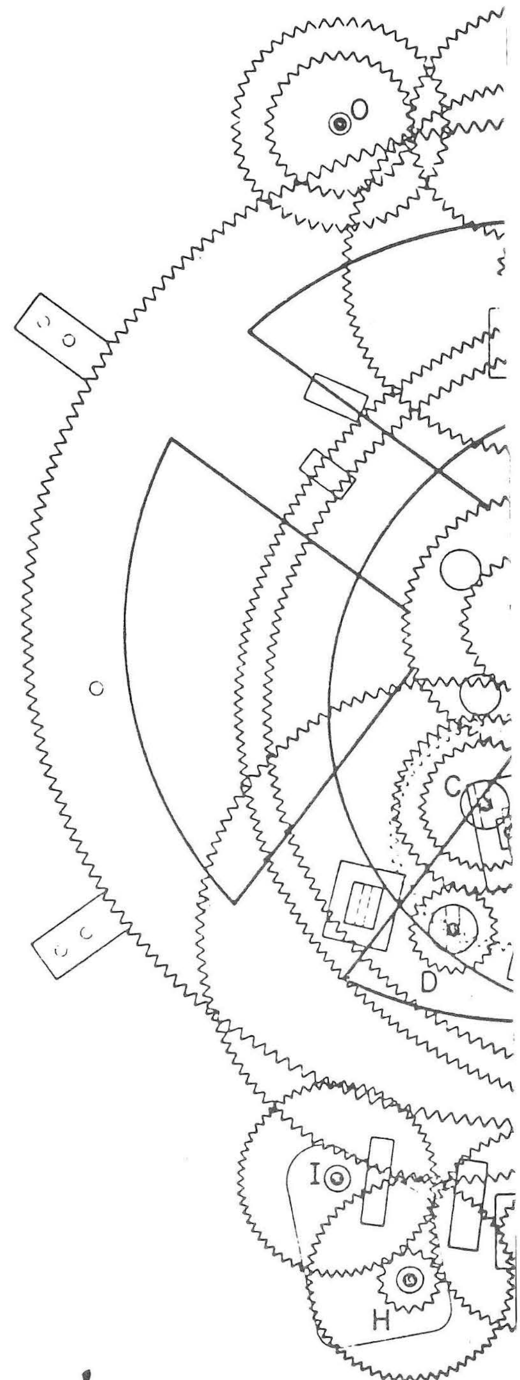

ON KNOWING HOW AND KNOWING WHAT

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My lecture this evening concerns the relation between making and knowing; between skill or craft or art--the Greeks called it _technē_--and contemplative knowledge; between knowing how and knowing what. I begin by attempting to sketch, roughly, three different, successive ways in which this relation has been lived or thought about.

First, a primitive stage, paleolithic, pre-agricultural. Certain relics of it, both living and non-living, have persisted into our time and world. Among the relics are, first of all, skeletal remains and tools, implements. Primitive humans were tool-makers. It was an amateur French geologist and antiquary, Boucher de Perthes, who in the 1840's and 50's first began to identify the chipped flint tools of the Old Stone Age, and to defend them for what they were before his disbelieving contemporaries. Then, since the 1920's, evidence has accumulated that humans were tool-makers even before they were human, that is, before they assumed the physical form of present-day _Homo sapiens_. It was not the brain that came first, but upright posture and the hand. When the hominid precursors of the human race came down out of the trees and walked upright upon the plains, they thereby freed their fingers and opposable thumbs for new uses, for the making and deployment of tools, weapons, utensils. The australopithecines of South Africa, with only 500 cubic centimeters of brain, no more than a chimpanzee or gorilla, were already walking erect and using stone implements. The more recently discovered remains of _Homo habilis_, "handy man", as his discoverers named him, show a brain of 800 cc, still not the normal size for _Homo sapiens_, which is 1200 to 1500 cc; but _Homo habilis_ is already, 3 and 3/4 million years ago according to Mary Leakey's recent find, an upright-walking tool-maker. The available evidence thus goes to show that the freeing of the hands for tool-making and tool-use preceded most human evolutionary brain enlargement. It looks as though the cerebral enlargement and the increasingly skillful use of the hands went together, the two developments reinforcing each other and yielding evolutionary advantage to the brainiest and handiest who were, so we can plausibly guess, the same.

The stone-age humans, then, came provided with the bodily and psychic equipment for seeing, grasping, and handling objects. We can guess that they were provided also with an exceptional capacity for learning. Coordination of hand and eye in handling objects, ability to learn new ways--these were what made possible the use of sticks and stones as extensions of human limbs. But probably we are thinking so far only of individual capacities; the true acquisition of a kind of tool by a group of hominids or humans implies that the making and using of it can be taught and learned, and so transmitted by tradition. There would have to be a continuing society, capable of transmitting tradition. And this is exactly what the archeological record reveals--continuity of traditions of tool production, lasting through millenia, with but minor changes.

Tool production was socially controlled. The implements of each type are practically identical in any given culture, over long periods and large areas. The hand-axes of figure 1, for instance, were shaped by a fairly elaborate process of chipping, a process that would take any one of us a pretty long time to learn. The hand-axe is believed to have been a general purpose tool, used mainly for cutting and scraping, as in skinning game. It seems to have been the predominant tool in the equipment of the early Stone-Age hunters. Its production and use started in southern Africa about a half million years ago, and then spread northward through Africa and Asia Minor and Europe over a period of several hundred thousand years, with only minor variations and improvements in technique. Hand-axes dug up at sites as widely separated as the Cape of Good Hope and London are indistinguishable except for their being made of different types of rock.

The traditional character of Stone-Age craft is also represented by the paintings made by Upper Paleolithic man in a hundred caves or so of southern France and northern Spain (figures 2 and 3). These were started about 30,000 years ago and were kept up for 20,000 years, with increasing refinement and detail and trueness to what is seen.

The paintings were painted, of course, by lamplight and from memory. The ordering of the paintings within the caves--bison, horses, and oxen in the central chambers; deer, mammoth, and ibex in outer areas; rhinoceros, lion, and bear in the farthest recesses--seems to be fairly constant, suggesting tradition-controlled practices. Among the paintings are occasional drawings of men dressed in the skins, horns, and tails of various animals, much in the manner of the medicine men or shamans in North American Indian tribes. This suggests a connection between the paintings and ritual magic, perhaps the preparation for the hunt.

But prehistoric skeletons and artifacts reveal very little indeed as to how the primitive looked out upon his world, and viewed his own role within it. There is another kind of evidence, the whole set of observations of ethnologists on pre-literate, stone-age peoples surviving into the present or recent past. To what extent these peoples have remained untouched by civilizations, past or present, may be uncertain, but certain characteristics appear to be common. The human communities are small, going to several hundred at most; within them, everyone knows everyone else. They are self-contained economically. There are no full-time specialists; even the job of shaman is a part-time one; for everyone must help with the task of food getting. The women, to be sure, have different roles from the men, seed-gathering, for instance, instead of hunting. The members intermarry and have a strong sense of solidarity. They think their own ways better than those of others. The Bakouris in central Brazil, for instance, have one and the same word for "we", "our", and "good", and another for "not we", "bad", "unhealthy". Men and women within the group are seen as persons, not as parts of mechanical operations. Groupings of people depend on status and role, not on mere practical usefulness. However pressing or demanding the business of survival, the focus is not on mere individual survival, but on the kinship unit, the personal nexus that joins human being, society, and nature in an endless round of birth, growth, decay, and rebirth. The central meaning of things lies in the linking of the deceased to the living and the yet unborn. The moral and sacred order predominates over the merely technical. The useful arts, with all the know-how they involve, are not isolated as merely useful or artful, but like an intense sport or dance or ceremony, form part of the sacred round.

As for knowledge, theory conceived as aiming at universal validity, it is absent. There is nothing for it to be of. There is no concept of a nature within which things happen according to regular, impersonal, cause-and-effect sequences. Natural events are interpreted as part of the communal life. Nature is though of as replete with spirits, acting by social norms which can be violated only at risk of retribution. The regularity of occurrences remains in the background, does not become a theme. The primitive human is alerted only if the event is a misfortune, or otherwise emotionally privileged; and then he traces it to an evil spell, or the enmity of a spirit, or a neglected ritual. But even here there is no rule-like regularity to follow in the interpretation. Everything is particular: this tree, this river, this animal, this man, this spirit. And spirits are capricious. A person may indeed attempt to exercise spiritual power over spirits; if he succeeds, he is a shaman, that is, a technician of the spirit. But woe to him who, having gained status as a shaman, fails in confrontation with another shaman to win the contest in the exercise of shamanistic power; shame, exile, possible insanity await him. The shaman's power is not founded in stable wisdom; its exercise is a risky affair.

Meanwhile, primitive consciousness is filled with knowledge, knowledge connected always in the most intimate way with know-how; knowledge in the mode of acquaintance with kinds of thing, kinds of material, kinds of process-how to coax fire into the hearth, how to use tension and twist to send the arrow hurtling through the air, and so on. Things, materials, and processes are silently recognized in their generic characters, and these recognitions form the tacit background for all the activities of everyday life. But the theoretical knower, he who would bring these things forward out of their tacitness into lucidity and articulation, has not yet appeared.

Second phase. This begins with the invention of agriculture. Knowledge and utilization of the reproductive cycle of plants brings a new kind of independence of external nature, a new set of possibilities and problems. Human life ceases to be parasitic upon the animals and plants that nature happens to provide. Foresight and planning must now extend through one annual cycle to the next. New and quite different techniques replace the old: the sowing of seed, hoeing, reaping, threshing, storing, grinding, baking, brewing. Permanent settlements become possible; people now live in villages. Within a relatively short span of time, considering the hundreds of thousands of years that paleolithic tribes had wandered the earth, within a very few thousand years, between 8000 and 3000 B.C., the agricultural revolution passes into the urban revolution. In the river valleys of the Tigris and Euphrates, the Nile, and the Indus, that which we call civilization first emerges.

Civilization means, in the first place, a number of things added to society: a marketplace, writing, a city, public control of irrigation, public works. Different civilizations develop away from the forms of folk society in different ways, but in all, there are certain features distinguishing them from primitive, folk communities. Kinship ceases to be the basis for the organization of society, and is replaced by residence. In other words, the state has come to be. As villages ball up into towns, and towns into cities, the members of society come face to face with diversity of beliefs and customs. Personal relations are replaced by impersonal, economic, utilitarian ones. Crafts become full-time occupations, often engaged in under conditions of lowly servitude. The old moral orders may persist in greater or lesser degree, but they necessarily suffer in the midst of recognized diversity. The common result is a state cult that draws into itself various elements of the old cults, in the effort to gain general acquiescence. Already there are those who are taking in hand the management of the moral order; these are the priests. Probably also there are scribes, those who master the calculative and notational skills required for the construction projects of the state and for the keeping of records. In brief, a literate elite has come to be, which separates itself from the world of the rural farmer and the town craftsman. The separation has been said to be fatal to science. But the literate elite, narrow-minded and self-serving though it often may be, has the function of maintaining the lore of mathematics and astronomy and the calendar. In Babylonia, between the 6th and 3rd century B.C., the sophistication of mathematical procedure and the accuracy of astronomical prediction became astounding.

Still, this was not science in our sense. Egyptian and Babylonian mathematics had nothing to do with ideas, or, in particular, with the idea of nature. At least in the west, this idea of an immanent order in the universe, independent of any arbitrary will, was first clearly articulated by certain wise men, legislators and merchant princes of the 7th and 6th centuries in the commercial republics that the Greeks established along the coast of Asia Minor. It is worth noting that these wise men express themselves in the language of the administration of justice and of commercial or monetary exchange. Anaximander puts it thus:

> That from which all things are born is also the cause of their coming to an end, as is meet, for they pay reparations and atonement to each other for their mutual injustice in the order of time.

And a century later Heracleitus is saying:

> All things may be reduced to fire, and fire to all things, just as all goods may be turned into gold and gold into all goods.

The second part of the statement refers to coinage, which was invented about 610 B.C. in Lydia. So human processes and artifacts are used to express the nature of nature.

It is a man from Ionia, too, who first challenges the popular and Homeric notion that the arts were given to men by the gods from the beginning. "The gods," says Xenophanes, "did not reveal to man all things from the beginning, but men through their own search find in the course of time that which is better." And Anaxagoras says: it is because man has hands that he became wiser than the brutes. Later on, the pre-history of the human race becomes a theme for the Sophists. Among the Greek thinkers generally, beginning with the Ionian philosophers and continuing down to Aristotle, the theories differ in detail and emphasis, but in all of them the past is viewed as the history of the progressive humanization of the animal man through the invention of the arts.

Now of all the Greek discussions of the arts, the one that will have the most influence in later times, and against which the initiators of modern science will stage their revolt, is the Aristotelian account. According to Aristotle, art <u>imitates</u> or <u>completes</u> nature. This formula undoubtedly has more than one meaning and application. One way in which the arts complete nature is in giving rise to leisure, which frees humans for what Aristotle regards as their highest function, the pursuit of knowledge or science. Aristotle says:

> As more arts were invented, and some were directed to the necessities of life, others to recreation, the inventors of the latter were naturally always regarded as wiser than the inventors of the former, because their branches of knowledge did not aim at utility. Hence when all such inventions were already established, the sciences which do not aim at giving pleasure or at the necessities of life were discovered, and first in the places where men first began to have leisure.

But how does art <u>imitate</u> nature? I think the fundamental meaning is as follows.

Things come to be, Aristotle says (and he is quoting a common view), either by nature or art or chance. Chance is an incidental cause; it means that something comes to be that could have come to be by design, but it occurred in fact by accident. Nature and art, on the other hand, are similar to one another, and unlike chance, in that each of them acts for an end. That nature acts for an end is most obvious, Aristotle says,

> in animals other than man: they make things neither by art nor after inquiry or deliveration. Wherefore people discuss whether it is by intelligence or by some other faculty that these

> creatures work,--spiders, ants, and the like. By gradual advance in this direction we come to see clearly that in plants too that is produced which is conducive to the end...If then it is both by nature and for an end that the swallow makes its nest and the spider its web, and plants grow leaves for the sake of the fruit and send their roots down (not up) for the sake of nourishment, it is plain than this kind of cause is operative in things which come to be and are by nature.

Both art and nature act for the sake of an end, but they differ in that nature is an internal principle of motion or change, in that in which it acts, whereas art resides essentially in a subject distinct from the material on which it acts. Art is characterized by a form or idea which is present in the soul of an intelligent being and is used to direct his activity; and this form is the form of the artifact or artful result that the artist or artificer aims to realize in the material. The arts are thus principles of change belonging to an exterior agent, like the idea of health in the physician which causes outside of itself the physical health in the patient. Nature is also a form, but is internal to the natural thing; it is like the doctor doctoring himself. The tree grows by an internal principle, the house is built by the external agency of the builder.

Now art is closer and more familiar to us than nature, for it is that by which we act on the world around us. It therefore serves Aristotle as a precious intermediary for the explanation of what nature is. Nature is less easily knowable to us than art, yet it is knowable--so Aristotle claims. To know the nature of a thing, according to Aristotle, we must grasp the what of it, its being-what-it-is. We can do this , he says, by means of the definition. Through the verbal formula of the definition the intellect knows, has present to it, the what of a class of things, say swallows, spiders, or trees. This is undemonstrable but nevertheless graspable knowledge, for according to Aristotle, there are forms in things which are knowable. The knowing of them constitutes the starting point for all further knowledge claiming universal validity.

Third phase. The founders of modern science rejected Aristotle's claim, and along with it they rejected the notion of art as imitating nature. They begin, on the contrary, with the assertion that, as between the products of nature and the products of art, there is no essential difference. As Francis Bacon puts it, "men ought...to be firmly persuaded that the artificial does not differ from the natural in form or essence..." Knowledge comes to be identified with making, cognition with construction. "We know the true causes only of those things that we can build with our own hands or intellect," says Mersenne in the 1620's. "To men is granted knowledge only of things whose generation depends upon their own judgement," says Hobbes in the 1640's. Meanwhile, there is a reappraisal of the practices, operations, and know-how of the arts called mechanical. Says Galileo:

> I think that antiquity had very good reason to enumerate the first inventors of the noble arts among the gods, seeing that the common intellects have so little curiosity....The application to great invention moved by small hints, and the thinking that under a ... childish appearance admirable arts may be hidden is not the part of a trivial but of a super-human spirit.

In the new way of looking at things, it is the <u>machine</u> which serves as the model of what can be understood and explained. What is a machine? That may not be so easy to say. The word "machine", derives from the Greek <u>mēchanē</u>, which means a contrivance for doing something, an expedient, or a remedy against ills. In antiquity the word in both Greek and Latin came to be applied particularly to devices for lifting weights, levers, pulleys, and the like. Also, in Lucretius' poem, the word <u>machina</u> is applied to the entire world in the phrase <u>machina mundi</u>, and this phrase reappears in Christian writers of the middle ages, with perhaps the connotation that the world is something made. But the machine that chiefly served as model and inspiration in the new science of the 17th century was a particular machine, invented some three centuries before: the weight-driven or mechanical clock.

Kepler,who in 1604 first introduced detailed mechanism into the theory of the heavens, wrote at the time:

> At one time I believed that the cause that moved the planets was a soul...I now affirm that the machine of the universe is similar not to a divine animated being, but to a clock...and in it all the various movements depend upon a simple active material force, in the same manner that all the movements of the clock are due to the moving weight.

A few years later, Descartes extends the metaphor to nature as a whole.

> There is no difference (he says) between the machines built by artisans and the diverse bodies that nature alone composes except the following: the effects of the machine depend solely upon the action of pipes or springs and other instruments which for the reason that they must have some proportion to the hands of those who build them are always so big that their figures and their motions appear visible, whereas the pipes or springs that produce natural effects are generally too small to be perceived by our senses.

It was on the analogy of clocks and mills that Descartes proposed to account for the functioning of all animals as well as the functioning of the human body. Controversy over Descartes' view of animals as machines provoked one controversialist to insist that "every Cartesian, in order to be consistent, should therefore affirm, with the same seriousness with which he affirms it with respect to beasts, that the other human beings who coexist with him in the world are machines." The claim that human beings are simply machines, and not in need of the immaterial rational souls with which Descartes had still seen fit to endow them, is at length asserted gleefully in the 1740's by Lamettrie, who concludes that life is solely for pleasure, becomes enormously corpulent and dies of indigestion at the court of Frederick the Great. But it is an altogether serious claim that Jacques Monod makes, in his recent book Chance and Necessity, when he affirms that all living things are chemical machines. In this pronouncement, I take him to be espousing the vast program of research that is molecular genetics.

I now turn to the consideration of certain machines. I shall try to make evident what makes them tick, what principles are involved. Later I shall return to the relation between knowing how and knowing what. I begin with the so-called mechanical clock, the great paradigm of the 17th century revolutionaries of science.

Instruments for keeping track of the daily passage of time have been known since very ancient times: wax candles and hemp ropes, certain lengths of which were supposed to burn in a definite time; sundials; sand-clocks; and especially water-clocks, which were in use in early Egyptian civilization and which from Alexandrian times, the third century B.C., onward, often assumed very elaborate forms, with special jack-work actuating puppetry to mark the passage of the hours. But the clock called mechanical was invented about A.D. 1300. See figure 4.

What you see here is an alarm clock of about 1400 from a monastery in Nuremberg. It rings the bell at settable times, and since the hand travels around the face in 16 hours, which is exactly the length of the longest winter night in Nuremberg, the presumption is that it was used to wake the sexton, so that he might in turn call the monks to read their nightly offices.

Before going to the heart of the mechanism, let me say a few words about the gearing, which transmits measured amounts of rotational motion from one part of the apparatus to another. There is nothing novel about gear wheels in A.D. 1300. Gearing was used in the windmill, (see figure 5), to change from a vertical plane of rotation to a horizontal plane of rotation; the windmill of this type was invented in the late 12th century, the earliest sure date for one being 1185, in Yorkshire. Twelve centuries earlier, similar gearing was already being used in water wheels (see figure 6), invented apparently in the first century B.C. But even more elaborate gearing was being made as early as the 3rd century B.C., by Archimedes and others, for calendrical computing machines and planetaria. In 1900 the sunken wreck of a Roman ship was found in the Aegean Sea by sponge divers; it has been dated to about 80 B.C. It contained, along with a lot of statuary, presumably destined for sale to the upper fluffy duff of Rome and other Italian cities, a peculiar mechanism of iron, badly rusted (see figure 7). Only in 1972, with the aid of X-radiography, was sense made of it; its gear ratios, it turns out, are based on astronomical constants well-known in antiquity. It is a calendrical computer, which was turned by hand, in order to find out where the sun, moon, and planets would be at given times. Similar types of gearing must have been used in a mechanism described by Cicero. He writes:

> ...When Archimedes fastened on a globe the movements of moon, sun, and five wandering stars, he, just like Plato's God who built the world in the Timaeus, made one revolution of the sphere control several movements utterly unlike in slowness and swiftness. Now if in this world of ours phenomena cannot take place without the act of God, neither could Archimedes have reproduced the same movements upon a globe without divine genius.

There is enough evidence to suggest a long tradition of geared calendar work and planetaria, starting with Archimedes and his contemporaries, transmitted through Islam to the West, and culminating in a number of clock-driven planetaria constructed in the middle of the 14th century in Europe. As far as the gear-work is concerned, the clock seems to come into being fully-fledged as a "fallen angel from the world of astronomy". The gear-work is one source of the clock, deriving from the heavens, but it still needs a terrestrial heart. By this I intend that which makes it, literally, tick. Look once more at figure 4.

On the left hand, at the top, you see a bell; our word "clock" comes from the French word "cloche" meaning bell. Below the bell, and slightly to the left, you see a wheel shaped something like a crown, and therefore called a crown wheel. Around its axle is wound a cord, which goes to a weight that you cannot see. Suspended by a string in front of the crown wheel is a vertical rod, called the verge, and at the top of it is rigidly attached a bell clapper. The way this bell-ringing mechanism works will be clearer in a moment. Now this bell-ringing apparatus, it seems, was first used just by itself. You released a catch, the weight began to fall, the crown wheel to turn, and the bell to be hammered by the clapper at the top of the verge. Out of one motion, the releasing of the catch, you got several motions, the bell rung several times: a helpful gadget for a sleepy or lazy bell-ringer.

But on the right you see another crown wheel, with another verge suspended in front of it, and atop the verge, a horizontal bar with weights on it, called the foliot, meaning "crazy dancer". The invention of the weight-driven clock consisted in seeing that the mechanism of the bell-ringing gadget, here on the left, could be used for a quite different purpose, to solve the problem of making a clock go by means of a weight. What is that problem? In 1271 Robert the Englishman wrote: "clockmakers are trying to make a wheel that will accomplish a complete revolution each day, but they cannot quite perfect their work." The difficulty was that the weight as it falls tends to accelerate, and so to make the clock go faster and faster. One could of course use a brake or some form of friction to keep the weight falling at a constant rate, but very quickly the rubbing surfaces would wear smooth, so that the speed of the clock would increase. The invented solution was what is called an escapement: in the case of the 14th century clock, it is a verge and foliot escapement. We shall see best how it works by turning to a simplified diagram; see figure 8.

Here the gear work has been eliminated for simplicity's sake, and the crown wheel has been replaced by a wheel with projecting pegs; both may be called 'scape or escape wheels. The previous picture did not show clearly the pallets or little plates that project from the verge above and below, in such a way as to mesh with the indentations in the 'scape wheel. Now suppose the 'scape wheel moving in the direction of the arrow. The peg at the top of the wheel is just striking the upper pallet. The motion of the wheel, and hence of the descending weight, is momentarily checked by the inertia of the system composed of verge, foliot, and the weights on the foliot. Then the driving weight slowly accelerates this system till the peg has pushed the top pallet out of the way, and has set the verge and foliot swinging counterclockwise as seen from above. For a brief moment the driving weight can fall freely. But now the swing of the verge and foliot brings the bottom pallet between the pegs of the scape wheel; notice that the bottom pallet projects from the verge in a different direction, something over 90° away from the direction of the top pallet. Almost immediately, the peg at the bottom of the wheel strikes the lower pallet. Now this peg at the bottom of the wheel has to be moving in the opposite direction from the peg at the top of the wheel, just because of the way wheels are. Hence the counterclockwise swing of verge and foliot is stopped, and the fall of the driving weight slowed again, until the verge and foliot are slowly accelerated into a clockwise rotation. Thus the fall of the driving weight is repeatedly interrupted by being compelled regularly to reverse the motion of the verge and foliot with weights. This is an instance of what is nowadays called negative feedback: a process produces an effect that slows down and thus regulates that very process. By means of it, the average overall motion of the weight, and hence of the clock, is rendered uniform.

So originated the weight-driven clock, through the invention of the escapement, which is literally what makes the clock tick. And this clock, suddenly, toward the middle of the 14th century, seized the imagination of the burghers and princes of Europe. Towns vied with towns to have in church or townhall the most elaborate set of planets wheeling, cocks crowing, angels trumpeting, and apostles, kings, and prophets marching and countermarching to the hourly booming of the bells. And also in the middle of the 14th century, Nicole Oresme, schoolman, bishop, adviser to the king of France, first enunciated the metaphor of the universe, or at least the supra-lunar part of it, as a vast mechanical clock--a metaphor that would later be extended to the whole world and become a metaphysics.

The fascination was with the mechanical marvel of the thing, with automatic, rhythmically self-acting machinery. Earlier I evaded the problem of defining the word machine. We need distinctions here, and with the invention of the clock, the automatic machine which is no longer a tool in the sense of a prosthetic instrument or extension of human limbs, I suggest we would do well to confine the term machine to devices that store energy, then release it in determinate ways, under various constraints and feedback mechanisms, so that particular purposes are accomplished. I should note that this term energy achieved its present-day sense only a little over 100 years ago; I shall come back to the problem of its meaning. By the constraints the stored energy is compelled to bring about certain determinate motions, either desired in themselves, as in the clock, or for the work they can accomplish. The criterion of a good machine is completeness of constraint: the parts of the machine should so connect as to eliminate all but the desired motions.

By this criterion, the 14th century clock was not very good, and in fact it needed a little old lady in a black smock to re-set it every day. The verge and foliot escapement in particular, must be criticized because its swing is stopped only by an impact between the pallets and the teeth of the crown wheel, and every such impact brings with it a recoil--a source of extra friction, wear and tear, inaccuracy. Moreover, the swing of the verge and foliot has no proper period of its own; its temporal span depends simply on the successive impulses that it receives, which are unlikely to be exactly equal.

Improvements came. From the 14th century onwards, the craft of clockmaking begins to flourish, to develop into skilled instrument-making, a craft combining mathematical know-how with expertness at the lathe and gear-cutting machine. The clockmakers and their offspring, the instrument-makers, will have a very great deal to do with the scientific and industrial revolutions of the 17th, 18th, and 19th centuries. Already in the 16th century they were producing tiny spring-actuated watches. But the difficulty about the verge and foliot escapement is met only in the 17th century, with two new inventions.

The first of these inventions is Galileo's and Huygens' replacement of the foliot by the pendulum; see figure 9. The verge is shown at the top of the drawing; it is now horizontal, at right angles to the pendulum to which it is rigidly attached. The advantage of the pendulum is that it has an almost constant, natural period of swing; the period approaches more nearly to constancy as the amplitude of swing is diminished. This clock is much more accurate than a verge and foliot clock, but unfortunately the verge with its pallets required a 40° swing to clear the teeth of the crown wheel, and with so large a swing, slight differences in amplitude make for noticeable differences in period.

The second invention reduces the angle of swing; see figure 10. This is the anchor escapement, invented apparently by Wm. Clement about 1670. Only part of the 'scape wheel is shown here. The bent lever above carries the pallets, and rotates from side to side on an axle that is rigidly attached to the pendulum's fulcrum. The arc of swing has now been reduced to 3° or 4°. With this improvement, and continued refinement of all moving metal parts to reduce recoil and friction, 18th century clocks could be made that deviated from their average rate by no more than 1/10 second per day.

Reduction of friction, elimination of impact and recoil, achievement of the smoothest working and greatest efficiency--these are machine-shop matters. But the concern with them, we shall see, leads to important conclusions: that the universe is not an eternal clock, and that change, not locomotion, is fundamental. This brings me to the second machine I shall examine, the steam engine.

The first practically successful steam engine was built by a provincial iron-monger, Thomas Newcomen, between 1702 and 1712. There had been various previous efforts to use the expansive force of steam, some of them going back to Hellenistic times. The trouble with these devices was that they did not develop much power. And this they did not do because the metallurgy was not available to make boilers and pipe joints that would hold steam at high pressure. A successful steam engine built around 1700 had to use low pressure steam. The solution was, to use it in conjunction with the weight of the atmosphere, which had been discovered by Torricelli and Pascal a half century before. We do not know how Newcomen came by his ideas, but in any case, his engine was an atmospheric engine. See figure 11.

This is the 1712 version of Newcomen's engine, hooked up for pumping water from a mine, the main use to which his engine was put.Below on the right is the boiler, just beneath the piston cylinder. When steam is admitted to the cylinder, the piston rises to the top, mainly because of the weight of the pump rod hanging from the other end of the rocking beam. Next, the connection between boiler and cylinder is closed, and cold water is sprayed into the cylinder, condensing the steam and so producing a partial vacuum. This allows the atmospheric pressure, acting on top of the piston, to force it back to the bottom of the cylinder, and so raise the pump rod. Then the next cycle is started by the admission of more steam. Notice that the force stroke is altogether due to the atmosphere; the steam pressure never rises much above one atmosphere of pressure. The working of these engines is said to have been accompanied by an extraordinary amount of wheezing, sighing, creaking, and bumping. They were compared, of course, to living things. They were dreadfully inefficient. By minor improvements, the thermal efficiency was approximately doubled by the 1770's, bringing it up to what we would now calculate as being about 1%.

More important improvements in efficiency were made by James Watt, during the last quarter of the century. As instrument maker to the University of Glasgow, he was asked in 1763 to repair a small model of a Newcomen engine, and was astonished by the huge quantities of steam required to make it work. Much steam was consumed just in heating up the cylinder, after it had been cooled down in the steam-condensation phase of the cycle. It would be an economy if the cylinder could be maintained always as hot as the steam entering it. "The means of accomplishing this did not immediately present itself," Watt says; "but early in 1765 it occurred to me that, if a communication were opened between a cylinder containing steam, and another vessel which was exhausted of air and other fluids, the steam, as an elastic fluid, would immediately rush into the empty vessel...." This was the invention of the separate condenser. See figure 12.

On the right is the boiler C; E is the piston cylinder, which is enclosed in a steam jacket; down below it is the separate condenser F, and beside it, the vacuum pump H which is operated by a rod and chain connected to the rocking beam. When the piston is at the top of its stroke, the exhaust valve to the condenser opens, and steam begins to be drawn from the cylinder into the condenser. Steam at about atmospheric pressure is simultaneously admitted to the cylinder above the piston, forcing the piston downward; the advantage of using steam rather than atmospheric air is that the cylinder stays hot. When the piston reaches the lower end of its stroke, the exhaust valve to the condenser is closed, the inlet valve that admits steam above the piston is also closed, and a valve is opened which allows steam to flow from the cylinder above the piston, through a pipe which is to the left of the cylinder, to the cylinder below the piston. The pressure on the two sides of the piston is thus equalized, and the piston rises, being pulled up to the top by the weight of the pump rod. The separate condenser led to about a three-fold improvement in efficiency.

Watt's further improvements were aimed not at efficiency but at making the steam engine an effective replacement for the water wheel, in delivering rotary power to factory equipment. See figure 13. I shall not describe this engine, except to point out that it had to deliver power in both halves of its cycle, and so be double-acting, and this required that the piston rod be rigidly connected to the rocking beam, and at the same time, that it be kept moving in a straight line--no mean problem to solve, but Watt solved it by the invention of what is called a parallel-motion linkage, and thereby initiated a whole branch of mathematical study. The large flywheel you see at the right helps by its rotational inertia to keep up a smooth delivery of power. Above the flywheel, to the left of its center, you see the centrifugal governor, whose speed of rotation is made to regulate the amount of steam entering the cylinder--another instance, like the clock escapement, of negative feedback.

What about steam engines for railway locomotives and steam boats? Engines for these purposes would have to be less massive than the Watt engine; but if they were to be a good deal smaller and still develop the required power, they would have to use high-pressure steam. Watt had always opposed the high-pressure engine, on the grounds that it was unsafe; and so high-pressure engines did not start to appear until after 1800, when Watt's various patents lapsed. The new engines were unsafe; life on the Mississippi and indeed the entire history of steam power from

1800 to 1850 was punctuated by appalling explosions. The new engines were also three and more times more efficient than any earlier engines. A variety of experiments were now undertaken to discover what the most efficient engine would be like. On what did efficiency depend? Was there a limit? If so, how could it be approached or attained?

These questions receive their first general answer in a small book published in 1824 under the title Reflections on the Motive Power of Fire. The author was a young man of 29 named Sadi Carnot. The thinking in this book was deeply influenced by the thinking in another book by another Carnot, Lazare Carnot, famous for his role in the military and political history of France during the 1790's, and also Sadi's father. In 1782, Lazare Carnot had written a book entitled Essay on Machines in General. In the preface he states:

> One of the most interesting properties of machines, which, I believe, has not yet been remarked...is that in order to make them produce the greatest possible effect, there must necessarily be no percussion, that is to say, that movement should always change by insensible degrees.

This, of course, is an ideal condition which is impossible to attain in practice, and can only be approached. The principle is nevertheless important. It accounts, for instance, for the superior efficiency of an overshot waterwheel as compared with an undershot water wheel. In the overshot wheel, the water drops into a bucket at the top of the wheel, and then acts on the wheel simply by its weight, rather than by its motion. In the undershot wheel, the water gains speed by descending along the stream bed, then impacts against the blades at the bottom of the wheel; but a good deal of the possible effect, about half, is lost in the eddies and turbulent motion of the water. Lazare Carnot had a formula for what was being lost; he called it live force--it was what we now call kinetic energy. And he shows that, in an ideal machine in which all friction, impact, and brusque motion is avoided, all the kinetic energy that is used up can appear as what we now call "work", measured by weight raised through a distance; he uses neither of the terms "work" or "energy", whose strict modern usage dates from the 1850's, but he has the ideas.

Now the way in which Carnot the younger at first makes use of the elder Carnot's work is as follows. Heat, thought Sadi Carnot, is like water, in that just as water tends of itself to flow downhill, so heat tends of itself to flow from the hotter to the colder body. And just as the waterwheel utilizes the live force of the descending water to do work, so, thought Sadi Carnot, the thermal machine does work by making use of the descending heat. Now the conditions for the maximum generation of power from the water wheel were that the water should enter the machine without turbulence and leave with velocity. Similarly, Carnot reasoned, the thermal engine would achieve its maximum effect if all the heat transferred from hot body to cold body had the effect of changing the volume of the gas or steam in the cylinder, and hence causing the piston to move; none of the heat should be permitted to follow its natural propensity of simply flowing from hot body to cold body without further effect. How could this condition be met?

See figure 14, which shows what Carnot imagined. Let there be a volume V_1 of gas or steam in a cylinder, its pressure being represented in the diagram by the height of the point A. Also, let the cylinder be in thermal contact with a reservoir of heat, such as a steam jacket that can be maintained at a constant temperature θ_1; and suppose the cylinder to be at a temperature only infinitesimally less than θ_1. Heat will then flow from the heat reservoir into the cylinder; the gas will expand; and the piston will move outward. It will move very slowly, of course, because the transfer of heat will be very slow, since the temperature difference between reservoir and cylinder is only infinitesimal. Never mind; we are concerned not with speed but with thermal efficiency, with getting the most for our expenditure on fuel; and while it may take several millenia for the locomotive to progress from here to Glen Burnie, we are in no hurry, of course, and can do a bit of extra thinking in the interim.

What I have been describing is the isothermal expansion indicated in the diagram by the line from A to B. It is the most efficient of all ways of getting work from heat, so why not use it, letting the gas expand forever? Of course, we would need an infinitely long cylinder, which is an inconvenience. Also, we had better note that as the gas in the cylinder expands, its pressure falls, in accordance with a well-known law called Boyle's law; the falling pressure is indicated in the diagram by the falling of the curve AB from left to right. By-and-by the pressure of the gas will have fallen to the level of atmospheric pressure, and then the piston will stop. So this won't do; what we need, clearly, is a series of processes in which the system is brought back to its initial state; that is, we need a cycle, so that the isothermal expansion can be started over again.

What about simply compressing the gas isothermally, back from B to its initial state A? This won't do, either, because we should have to do just as much work in compressing it as it had originally performed in its expansion. Those of you familiar with plots of pressure against volume of a fluid know that the area under such a curve represents work performed; and of course the area under the curve AB, namely V_1ABV_2, is just the same as the area under BA, the same curve traversed in the opposite direction. We need to return the gas to its initial state by a less costly route. The solution to the problem is called a Carnot cycle. Here is the way of it.

Stop the isothermal expansion at B, while the pressure of the gas is still above atmospheric; remove the cylinder from contact with the heat reservoir at temperature θ_1, and immediately insulate it thermally, so that no heat can pass in or out; then let the gas expand further. Because heat is not allowed to pass in or out, this further expansion, from B to C, is called an adiabatic process. Note that the adiabatic curve is much steeper than the isothermal curve; this means that the temperature is dropping as well as the pressure. Let there be a cold reservoir, containing, say, ice and water at temperature θ_2, and let the adiabatic expansion continue until the gas almost reaches this lower temperature, or is infinitesimally above it. Next place the cylinder in contact with this cold reservoir, and compress the gas from C to D. During the isothermal compression from C to D, we are having to do work on the gas, and heat is flowing out of the cylinder into the reservoir. However, we do less work than we would have to have done to compress the gas at the higher temperature. Finally, compress the gas adiabatically from D to A, so that its temperature rises to the original temperature θ_1, and its pressure and volume assume the original values indicated by the point A. We are now ready to begin a new cycle.

What have we gained? A certain amount of heat has been taken from the hot reservoir; call it Q_1. A certain net amount of work has been done by the engine, say, in raising a weight; call it W. W is the difference between the work the expanding gas does, represented by the area V_1ABCV_3 and the work done on the gas in compressing it, namely V_1ADCV_3; evidently the net work is represented by the area of the curvilinear quadrilateral ABCD. For an expenditure of coal or oil or wood yielding the heat Q_1, we have gained the work W. And Carnot asserts that no thermal engine working between the same two reservoirs at temperatures θ_1 and θ_2 could be more efficient.

Carnot proves this assertion, but before showing how he does so I wish to correct an error that his argument contains, one which follows from the analogy of the waterwheel. He assumes that all the heat Q_1 that enters the cylinder during the isothermal expansion from A to B also leaves the cylinder during the isothermal compression from C to D; he assumes, in other words, that Q_1 is equal to what I have labelled Q_2. Actually, the energy to do the work W is extracted from the heat Q_1, and so W is equal to Q_1 minus Q_2. This conclusion, or its equivalent, was reached simultaneously by more than a dozen Europeans thinking and experimenting independently during the 1830's and '40's; Sadi Carnot himself reached it before his early death in 1831. Natural philosophers were pushed to it both by a conviction in the unity of nature, and by a variety of observed instances of what we would now call transformations of energy. What is this energy that is being transformed? All that can be said, I believe, is that it is something capable of doing work, capable of raising weight through a distance, and as such capable of being treated quantitatively. There is no single mathematical formula for it. But the postulate that there is this entity called energy which is conserved in all the transformations of nature has come to be basic in all scientific accounting, all our dealings with nature, all scientific thought about the economy of nature. It is called the first law of thermodynamics.

Now for the proof, appropriately corrected, of Carnot's theorem, see figure 15. The efficiency of Carnot's engine is given by $\eta = W/Q_1$, where we can measure work and heat in the same units of energy. Let there be, if possible, a more efficient engine, working between the same heat reservoirs, and let it produce the same amount of work W while extracting from the hot reservoir a smaller amount of heat, Q_1'. Then its efficiency will be $\eta' = W/Q_1'$, where Q_1' is less than Q_1, so that η' is greater than η. Now let us use this more efficient engine to run the Carnot engine in reverse, which we can do, since all the processes that go on in the Carnot engine are reversible. Run in reverse, the Carnot engine becomes a refrigerator; a net amount of work W is put into it; it extracts heat Q_2 from the cold reservoir and rejects the larger amount of heat Q_1 to the hot reservoir. And to run the Carnot engine in reverse, we can use the work W produced by the new and supposedly more efficient engine, which I have labelled I in the diagram. Coupling these two engines together in this way, we obtain a rather peculiar device. There is no net input or output of work. Heat, in amount equal to $Q_1 - Q_1'$, is extracted from the cold reservoir and rejected to the hot reservoir. That is all. This result does not violate the first law of thermodynmanics. Yet surely, Carnot and the physicists who followed him judged, it is impossible; heat of itself does not flow up a temperature gradient. And therefore Clausius and Kelvin in the 1850's formulated a law, the second law of thermodynamics, of which this result would be the violation. As Clausius put it:

> It is impossible to construct a device that, operating in a cycle, will produce no effect other than the transfer of heat from a cooler to a hotter body.

Let me now try to formulate the main implications of this law and of the reasonings that accompany it.

First, as we can see from the diagram of the Carnot cycle, it is never possible to convert any quantity of heat completely into work, without further effect; some of the heat must always be ejected to a colder reservoir. This means that, even in an ideal heat engine, the efficiency is always less than 100%. I mention in passing that the efficiency depends on the temperatures of the two heat reservoirs, and is improved by raising the temperature of the hot reservoir and lowering that of the cold reservoir. This accounts in part for the superior efficiency of the high pressure steam engine, which provides a higher difference in temperature between the boiler and the atmosphere.

Secondly, the Carnot engine represents an ideal limit; no actual engine can reach that limit, or come close to it. The temperature difference between reservoir and cylinder cannot be made infinitesmial. The adiabatic containers never insulate perfectly. Always some of the heat follows its natural propensity and flows from the hotter to the colder bodies without causing any motion of the piston, without doing any work. This means that if a heat engine does some work, raising a weight, say, and if we then undertake to have the weight fall and the engine run in reverse as a refrigerator or heat pump, in an effort to restore the exact initial conditions from which we started, we will not succeed except by investing extra energy in the process. In this sense, the processes that go on in the heat engine are irreversible.

Thirdly, by a series of particular arguments dealing with each kind of process encountered in the world, chemical, electrical, nuclear, and so on, it results that all natural processes are irreversible, in the sense just explained. In each case, some heat is dissipated, and the reversal of the process would require that we extract this heat and convert it completely into work done, say into the lifting of a weight, without any further effects ensuing. But this would violate the second law of thermodynamics. Each process, then, has a natural direction, towards a more stable configuration or state. To be sure, any given process may be run in the reverse direction, by making special arrangements,but these always involve the irreversible expenditure of available energy. If we consider all the changes that occur in the surroundings as a result of any process, then the second law assures us that of the total energy with which we began, some will have become unavailable for the production of useful work. As a measure of the transformation of free into unavailable energy, the physicists use a quantity called entropy, which increases as the transformation proceeds. If in any natural process we consider all the energy exchanges involved, we find that the net result is an increase in entropy. By computing the changes in entropy in any process, we can determine its natural direction, which is the direction of entropic increase.

From any one moment, then, to any later moment, the world changes irreversibly. Perhaps we are in some sense aware of this, just in being aware of being alive; but it is a different matter to assert it as a fundamental fact of natural science. A number of physicists during the 19th century felt the 2nd law of thermodynamics to be disturbing, and attempted to reduce it to mechanics, that is, to derive it from mechanics. But this cannot be done, for the simple reason that the equations of mechanics are indifferent as to whether time runs backwards or forwards, and therefore irreversibility is not derivable from them. What the physicists in fact did was to construct a kind of analogue to thermodynamics, called statistical mechanics. It turns out to be quite as irreducibly and fundamentally statistical as it is mechanical. The kind of statistics used must be chosen so as to fit the system studied, and lead to the known empirical consequences that thermodynamics predicts. In any case, the second law remains, as Eddington called it, "time's arrow", signifying not how fast change will occur, but the overall direction in which it will irrevocably go, toward configurations that we may call more stable.

Thermodynamically, then, the world changes irreversibly; but in special circumstances, it appears that it does so in ways that especially interest us. Let there be, for instance, a sun, radiating energy unremittingly into the unfillable sink of outer space. But in its flow from hot to cold, let some of the energy pass by way of an earth, an assemblage of certain chemicals, a temporary trap for the energy in its inevitable entropic descent. In such case, Morowitz has recently argued, with high probability the improbable happens; that is, order arises--symmetry, cyclical transformation, process that has a shape and pattern. Matter which left to itself, in the dark, without a sun to shine upon it, remains inanimate, random, chaotic, now under the surge of solar energy is transformed into an ordered dance of living forms. Are they forms that we will recognize, feel convivial with, if it comes to be the point of our being introduced? Or is life as we know it a very unique thing, perhaps a species of some more inclusive genus, but nevertheless a quite distinct species? The question is very speculative, but if one examines the delicate balance of conditions our earth has enjoyed up to now, and if one considers the extent to which chance events, events that were not determined mechanistically to happen, have entered irreversibly into biological evolution, then the likelihood that human-like beings exist elsewhere in the universe looks small, nothing worth gambling on. Living systems could have employed right-handed proteins, instead of left-handed ones, and perhaps that would have made little difference. But the evolution of the human brain, into which thousands of irreversible events have entered, has happened only once that we know of; and the alternative possibilities seem countless. A conclusion on which I expect us therefore to agree is that life-stuff as we know it, and the biosphere within which and with which it evolves, are to be cherished as our proper heritage. And thermodynamics, wearing the human smudge and sharing the human smell, is the economic science that must guide us in the management of this our household, warning us of the irreversible character of our transactions with nature, the finitude of the resources upon which we draw, the ineluctable price of degradation of energy that must be paid for every maintenance or achievement of order or form or value.

I have been engaged in what can have seemed a long digression from my original theme, but I think I am not too far from my starting point; something that also happens with random walkers. Modern science in its inception, I have said, set up for itself the program of science as construction, the sublimation of our age-old capacities for lifting, heaving, pushing, pulling, taking apart, rearranging. Perhaps there is something inescapable about our imagining that program as carried to completion--the completed description of the world and of ourselves as an assemblage of spatially and temporally located, deterministically interacting parts--a machine. Yet surely the result is bizarre, a bad metaphysical dream, a world of bare fact from which problems and persons, learning and knowing and valuing are absent.

If asked to argue against this image on the basis of scientific results, I should say that there are no doubt certain bridges over which the effects of molecular happenings--the deterministic ones and also (please remember!) the chanceful ones--move into our world of sweet and bitter, hot and cold, painful and pleasurable, clumsy and skillful. And I should propose that if chance has acted in the development of the biosphere, it must also be active in the normal functioning of the living body and can be expected to lead to its most significant effects in the functioning of the human brain. Long ago Epicuros, knowing that otherwise knowing and willing were impossible, postulated an alternative to necessity in the swerve of the atoms. The present-day version of that alternative in physics allows us to speculate how decisions and deliberations utilize (but do not constitute!) the chance-like forking of the causality of elementary events, how morally and logically a chance of alternative sequence can become significant in allowing us to will yes or no, to give way to or to "stand up to temptation". Of course I do not know this; it is speculation.

Less speculatively, I would re-direct your attention from the constructed, or what is assumed to be constructed, to the constructing, that is, the practice of skills that is everywhere entwined in the activity of science. Now these skills involve, to begin with, the use of our body and of tools. Our own body is the only thing in the world that we never normally experience as an object; we experience it rather in terms of the world to which we are attending from our body. It is by making this intelligent use of our body that we feel it to be our body, and not simply an object. When we adopt a tool for use, we transform it from an object into a sentient extension of our body. Suppose, for instance, we are using a probe to explore a dark cavern. If we are using it for the first time, we feel its impact against our fingers and palm; but as we become accustomed to its use, our awareness of its impact on the hand is transformed into a sense of its point touching the objects we are exploring. We become aware of the feelings in our hand in terms of their meaning located at the tip of the probe or stick to which we are attending. We attend from the feelings in our hand to their meaning at the tip of the probe. So, in the exercise of this and other skills, there is a tacit background of perception and rule-following, and a focal awareness directed to an object.

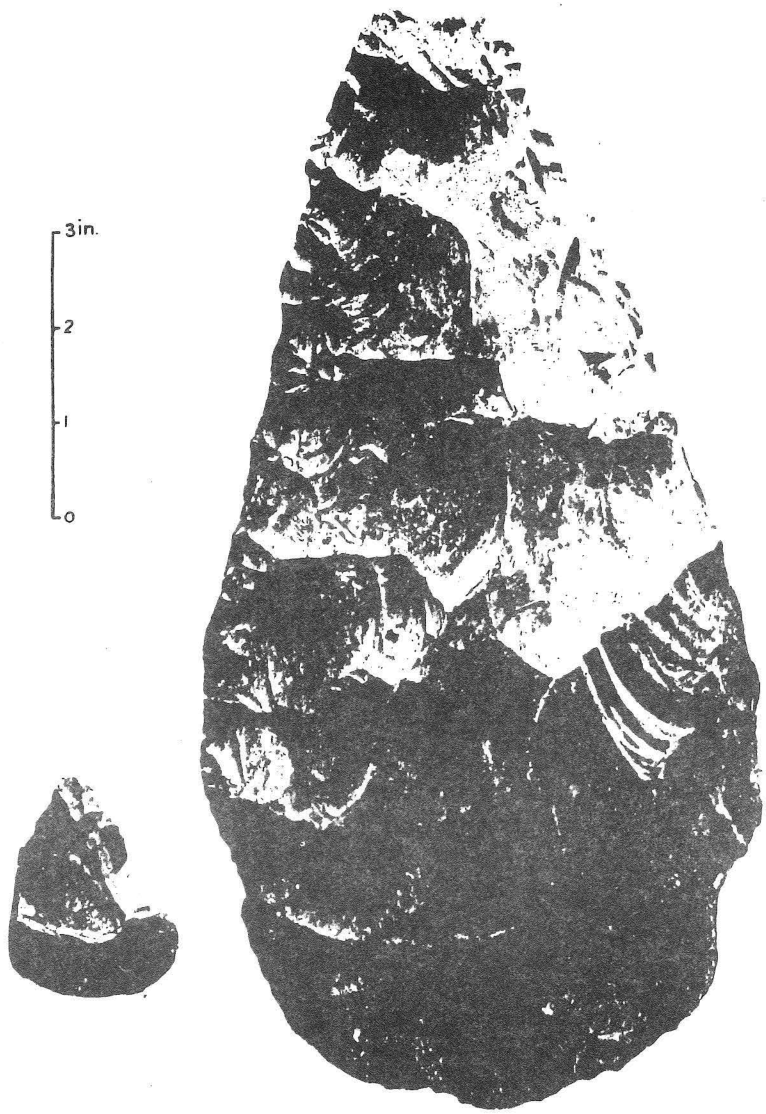
Similarly, in the vocal expression of a thought, I rely on an ability to produce syllabic sounds, on an acquaintance with vocabulary and a grammatical skill in stringing words together to form sentences, but all of this muscular and linguistic know-how is tacit and subsidiary to the meaning that I am attempting to convey. All thought contains components--rules that are being followed, perceptions, dispositions to act or respond--on which we depend but of which we are not focally aware. Thought dwells in these components as if they were parts of our body. Thinking is not only of something, though it is always and necessarily that; it is also fraught with the roots from which it springs. Like a muscular skill, it has a from-to character.

So do we keep expanding our body into the world, by assimilating to it sets of particulars which we intergrate into comprehensive entities. So do we form, intellectually and practically, an interpreted universe populated by entities, the particulars of which we have interiorized for the sake of comprehending their meaning in the shape of the wholes to which they belong.

So do we recognize a problem, Meno's paradox to the contrary notwithstanding; to recognize a problem is to recognize that something is present though hidden; it is to have an intimation of the coherence of hitherto uncomprehended particulars.

So also do we come to recognize a person, in a gesture or in the performance of a skill. Indeed, we cannot recognize a skill unless we understand that we are faced with a coordinated performance, and proceed to pick out the features that are essential to it, the action that is at work within it. So we get to know the intimate parts of a skill and the powers of the person behind it.

Finally, what about objectivity, objective science in the view I am taking? I should answer, first, that we stand on no platform, from which a strictly detached knowing is possible. The zero-point of our history is not accessible to us; even as knowers, we are subject to irreversible time. But standing within our world, the world that has come to be for us, we can once more entertain, following the example of certain Ionians, the idea of knowing as universally valid, true knowledge as a ideal, limiting notice. This will be a moment of suspension of practical activity. It will be a moment of wonder, in which there emerges the idea of the essentialwhatness of things, their being. To entertain the idea of such knowing is to enter consciously a tradition that is embodied but dormant within us; it is to accept, not a model, but an unfinished and unfinishable task. To seek to uncover the original meaning of this idea is an essential step toward the discovery of what we are.



Acheulian hand-axes from Furze Platt near Maidenhead.

FIGURE 1

FIGURE 2: Cave Painting

The red deer, below, frequently painted on the walls of Lascaux, was probably one of the principal food sources of the inhabitants of the area. Now restricted to mountainous and forested regions of Europe and Asia, this deer species—of which the North American elk is a variety—formerly inhabited diverse environments.

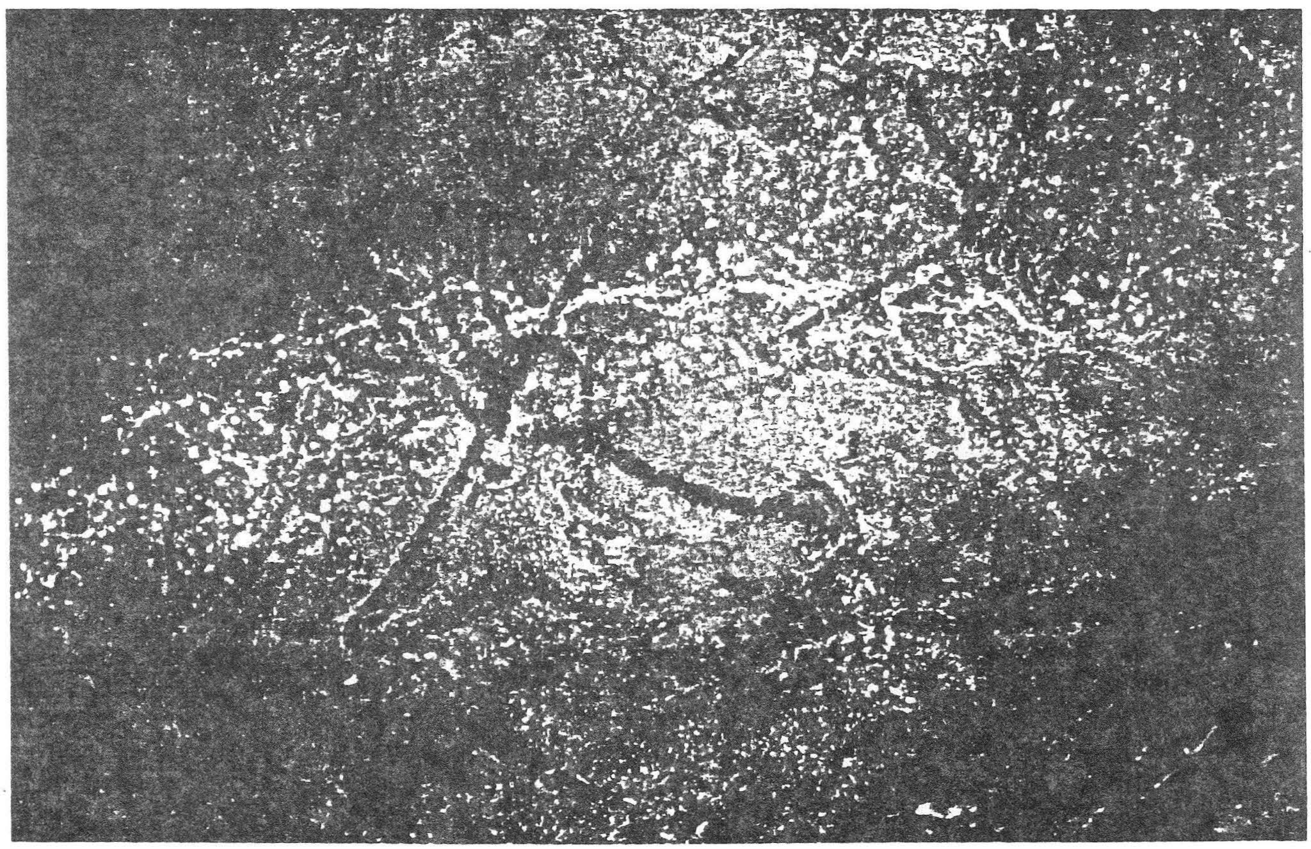


FIGURE 3: Cave Painting of Wild Ox or Aurochs

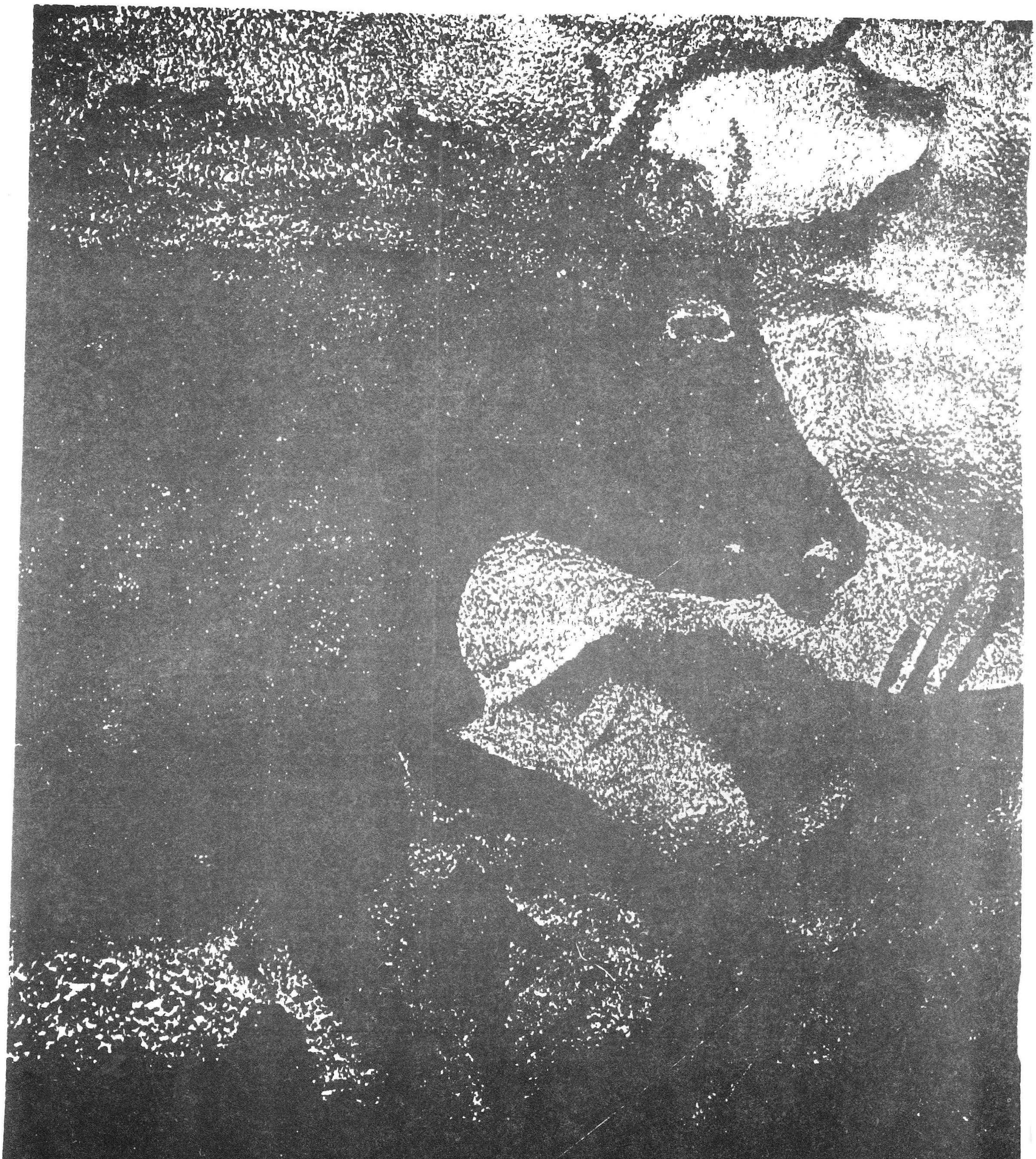


FIGURE 4: Early Gothic Alarm Clock, c. 1400, from Church of St. Sebaldus in Nuremberg

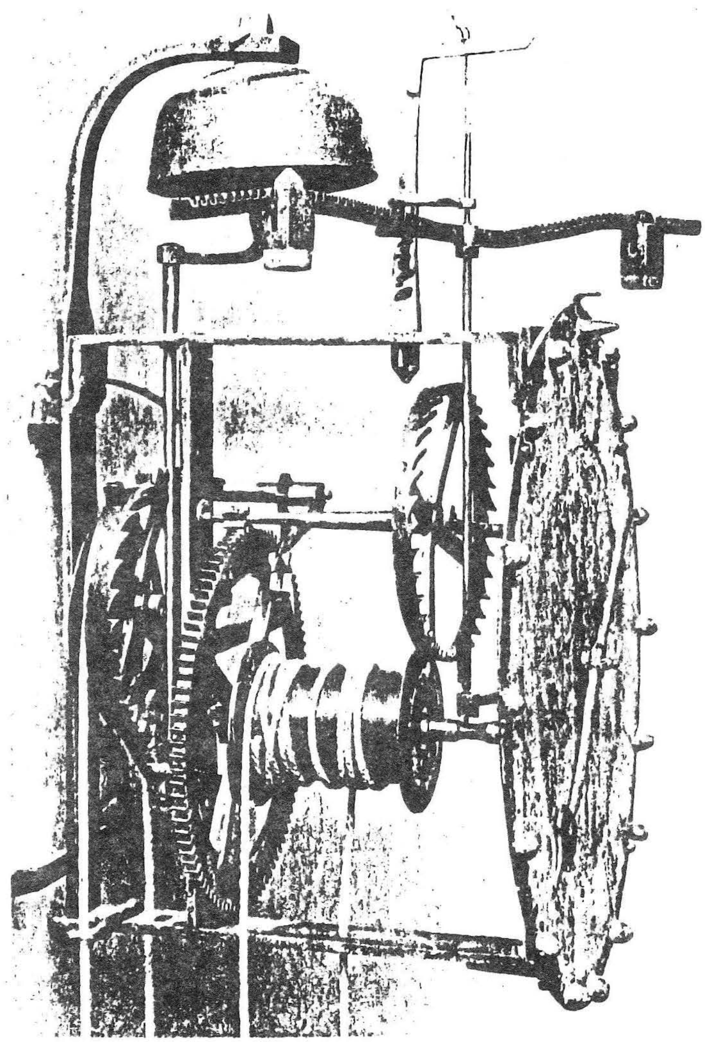


FIGURE 5: Post Windmill
(the diagram is of the 16th century)

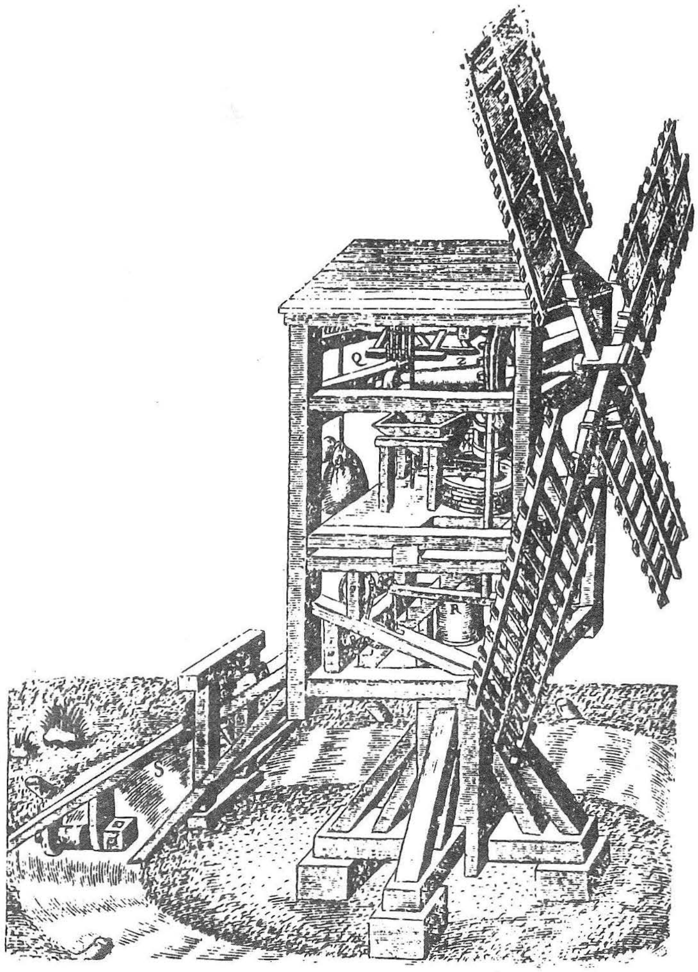


FIGURE 6

Roman mill with gears:
after Vitruvius.

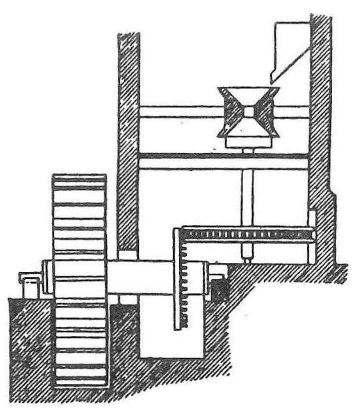
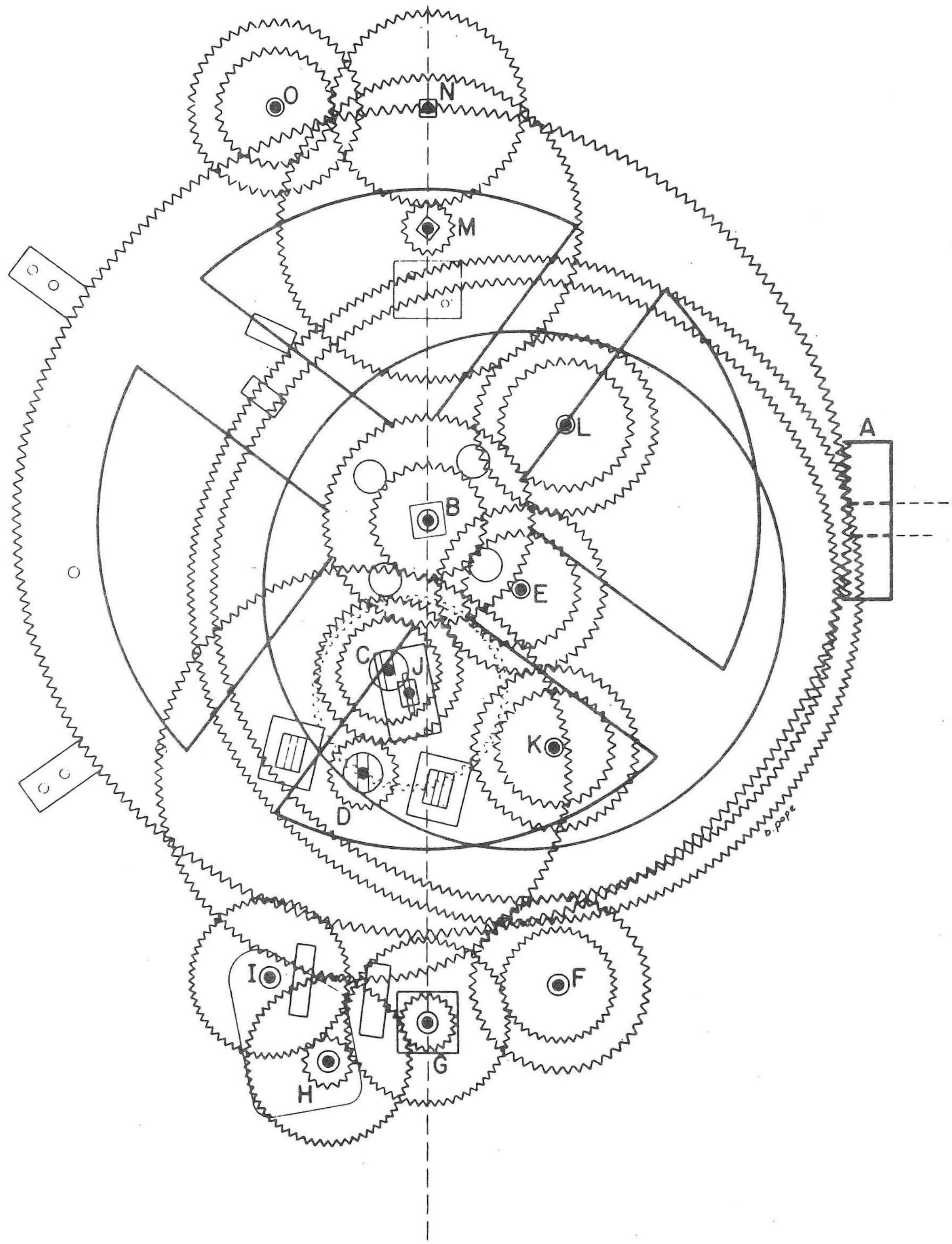


FIGURE 7: Calendrical Gearing from Calendar Machine, 1st century B.C.



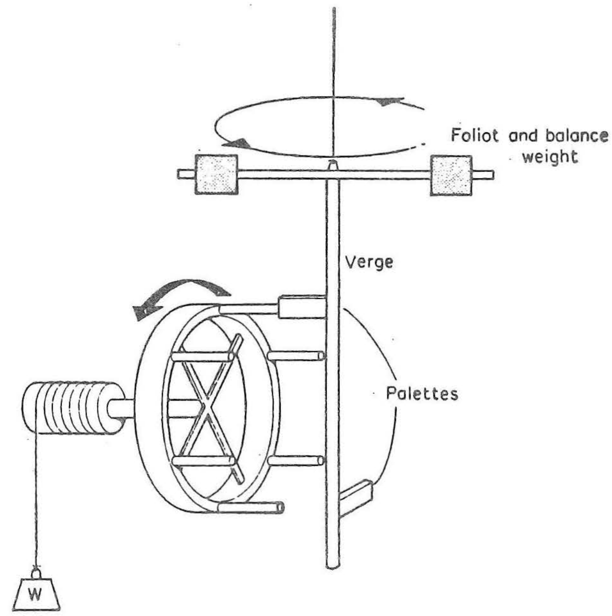


FIGURE 8: Simplified Diagram of verge and foliot escapement

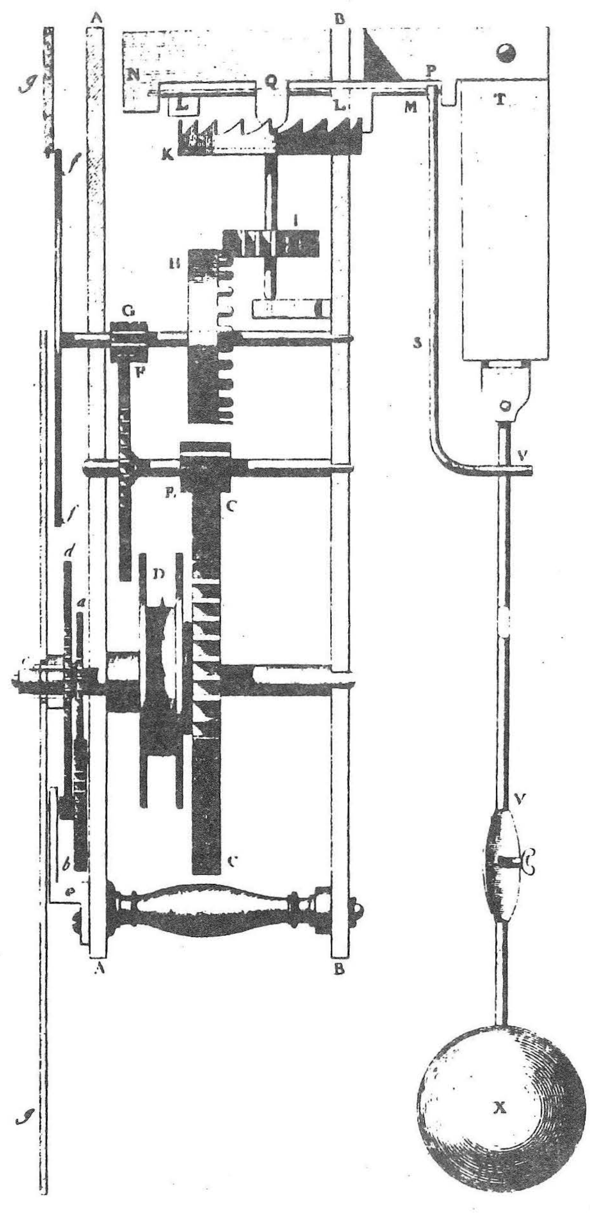


FIGURE 9: Combination of pendulum with verge and pallets introduced by Galileo and Huygens

FIGURE 10: Anchor Escapement with Pendulum
introduced by William Clement

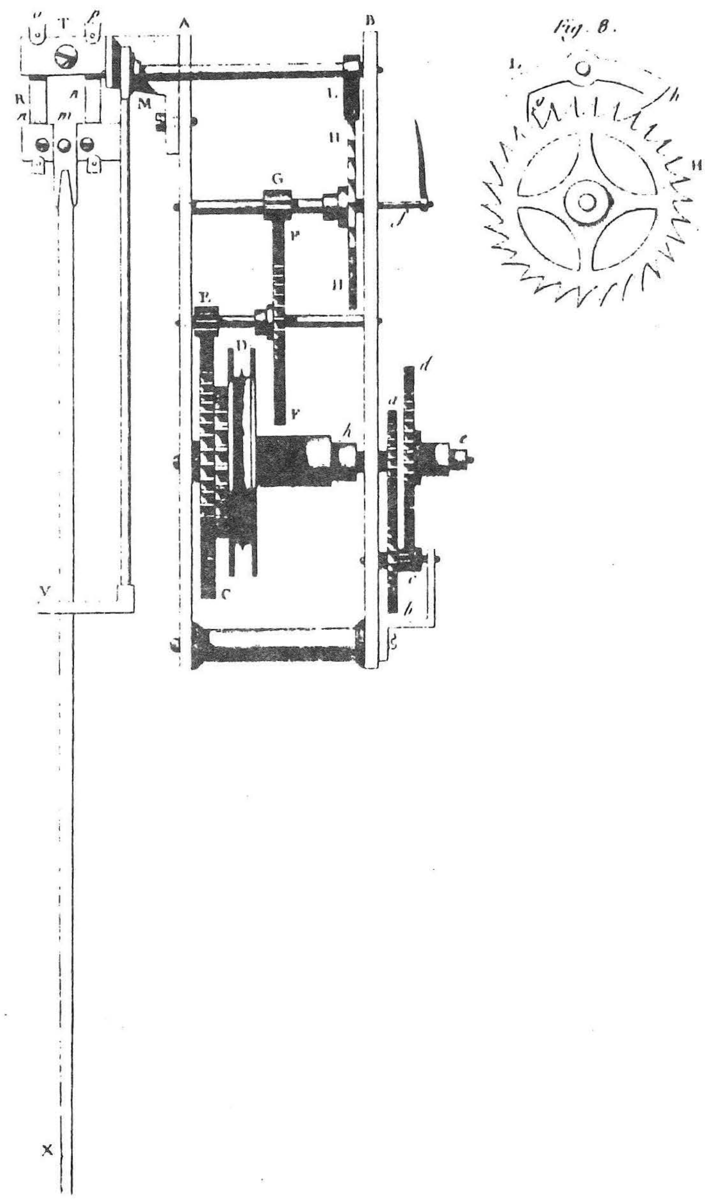


FIGURE 11: Newcomen's Atmospheric Engine of 1712

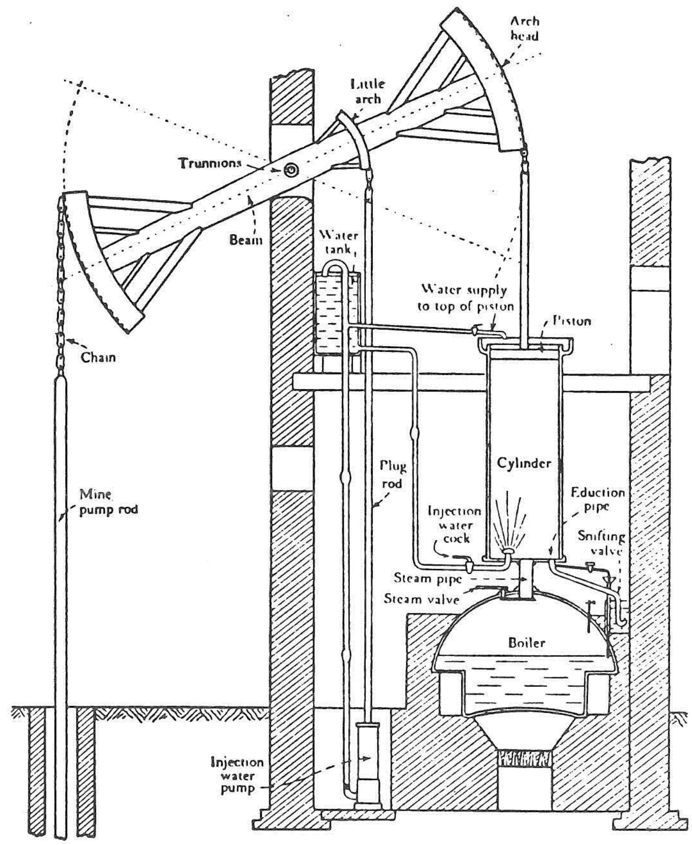


FIGURE 12: Watt's Single-Acting Engine with Separate Condenser

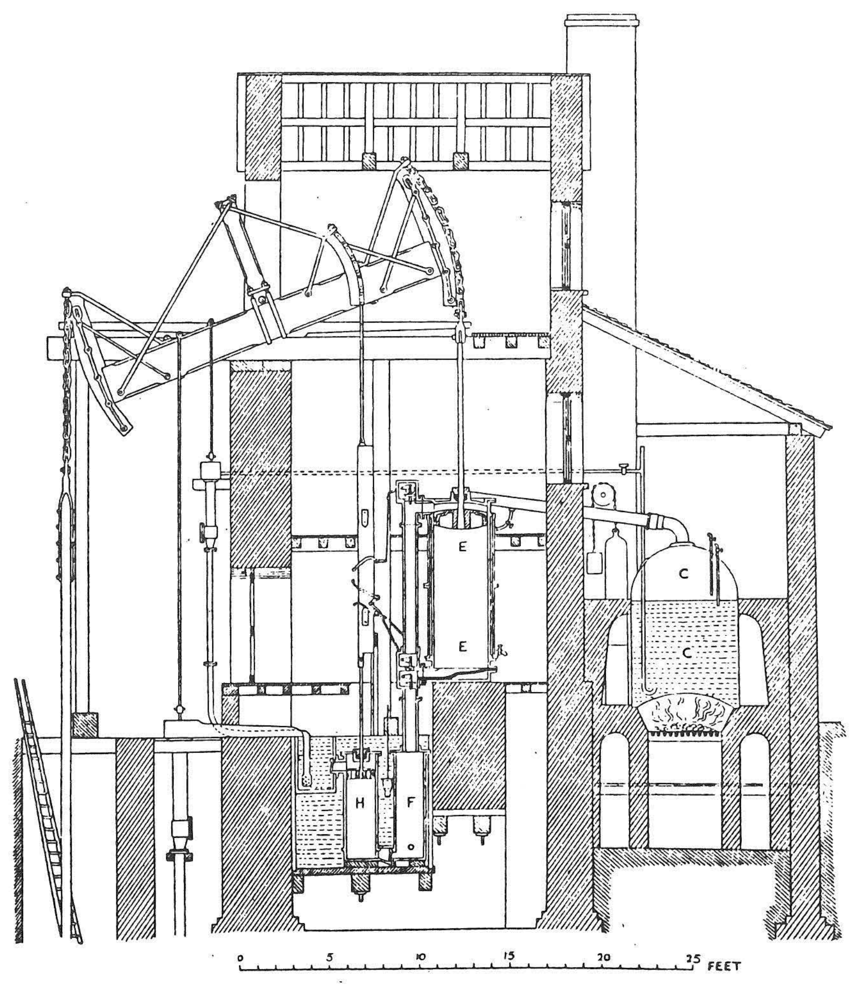


FIGURE 13: Watt's Double-Acting,
Rotative Engine

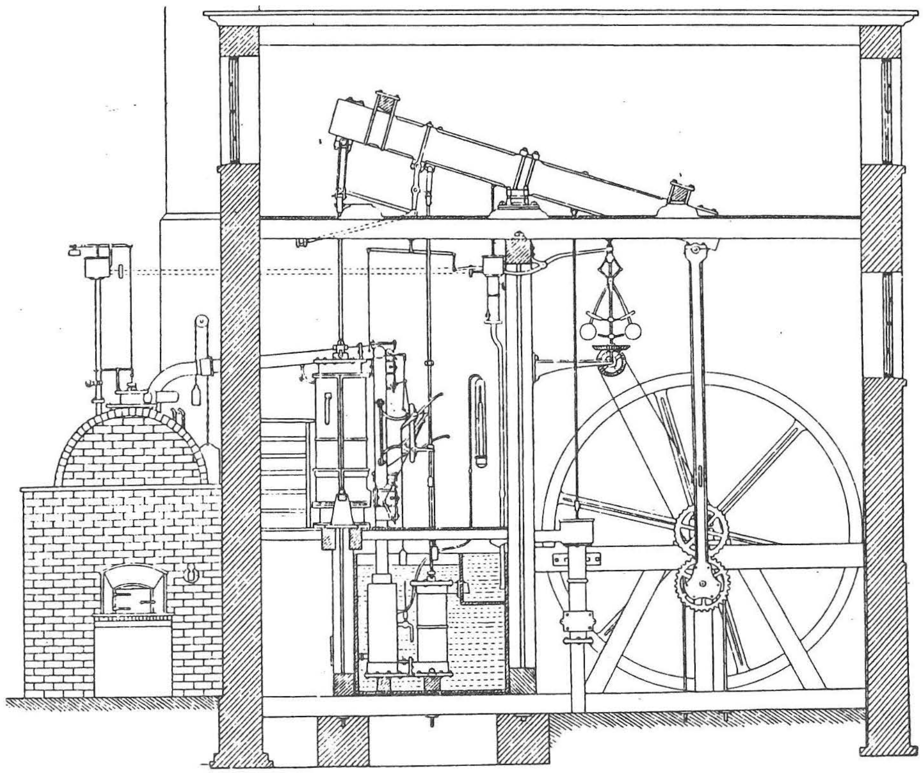
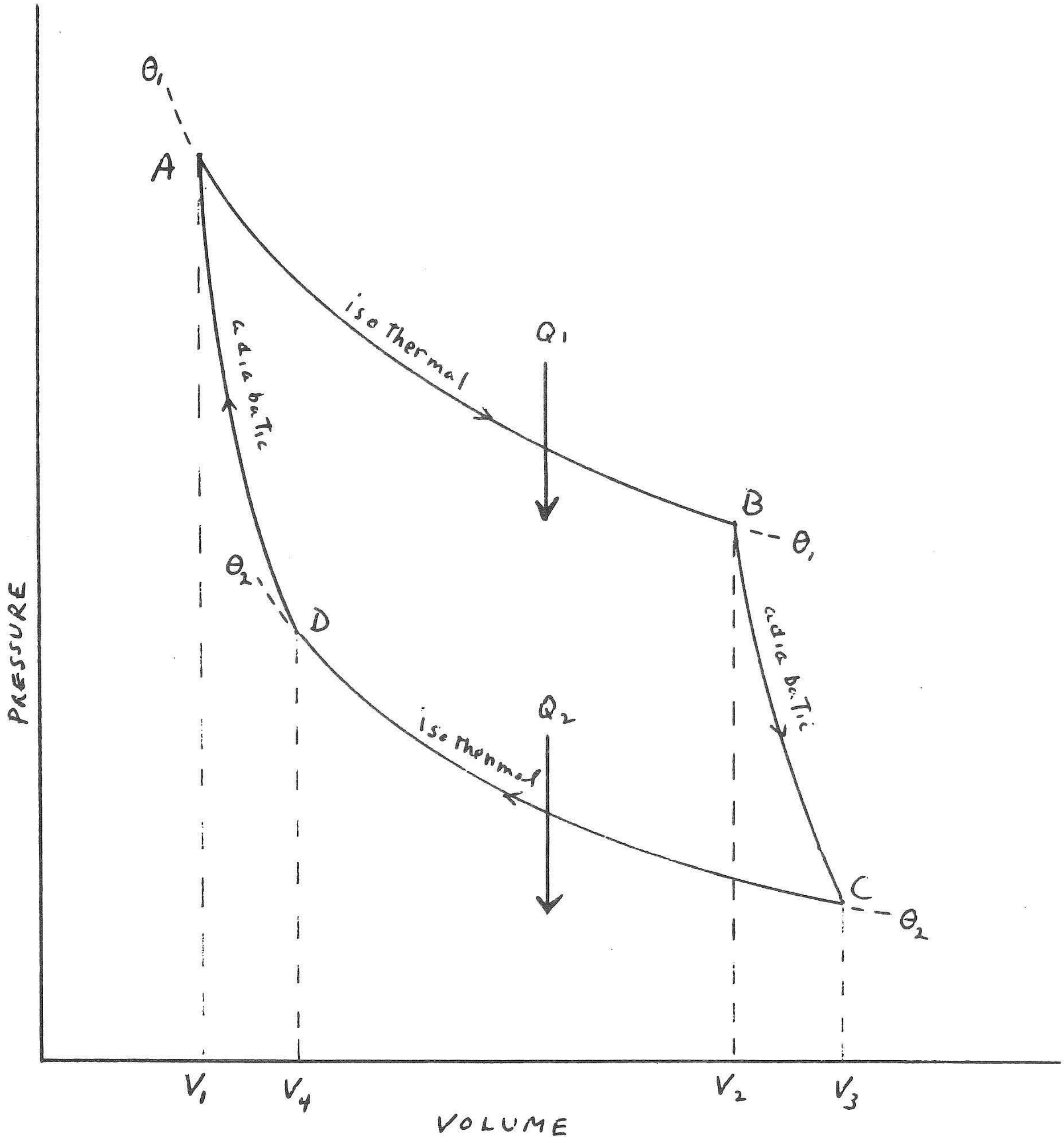


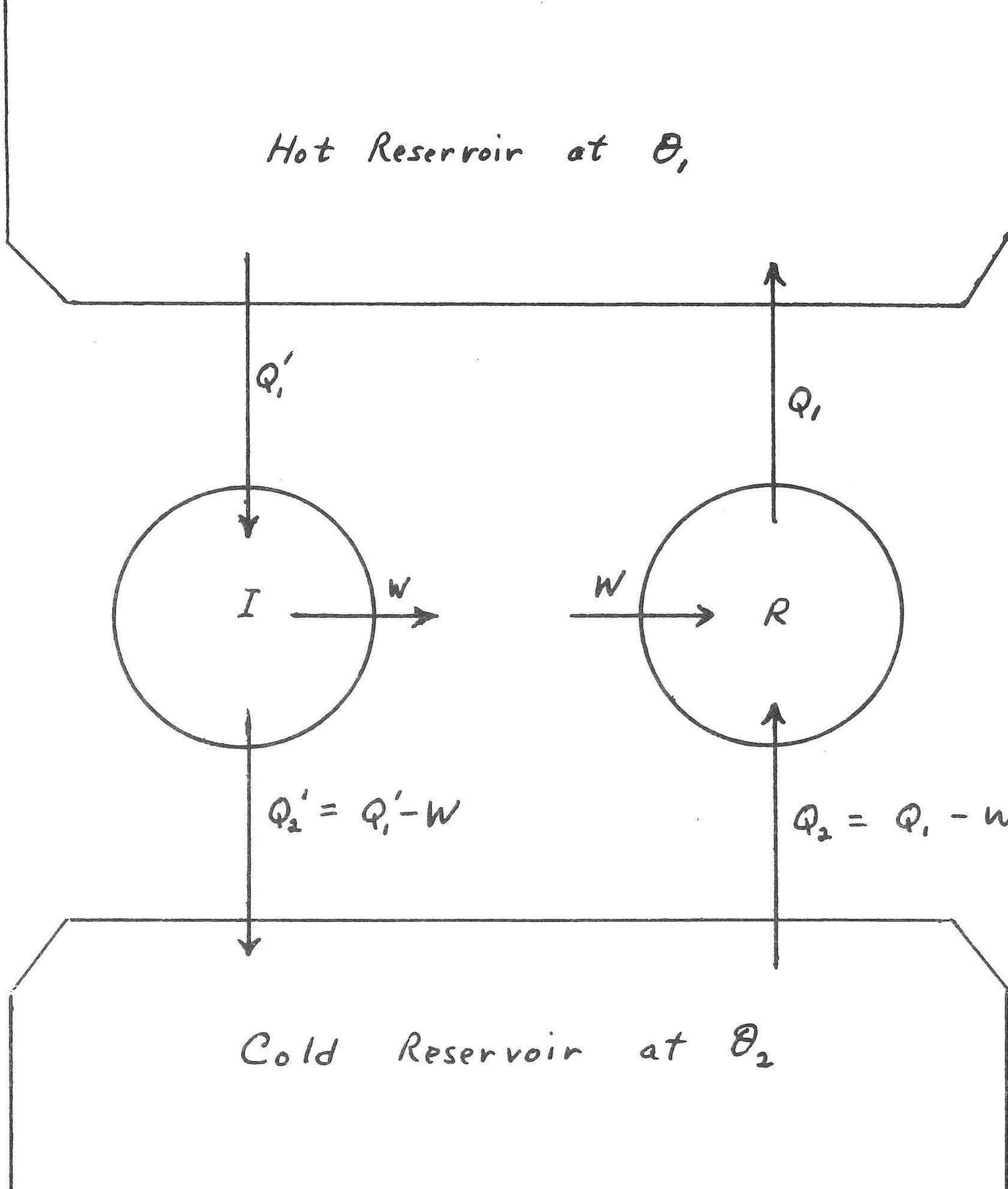
FIGURE 14: The Carnot Cycle



$$W = Q_1 - Q_2$$

$$\eta = \text{efficiency} = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$$

FIGURE 15: Carnot's Theorem



Assume $\eta' = \dfrac{W}{Q_1'} > \eta = \dfrac{W}{Q_1}$

Therefore $Q_1' < Q_1$

Net heat extracted from cold reservoir

$= Q_1 - W - (Q_1' - W) = Q_1 - Q_1'$

Net heat delivered to hot reservoir

$= Q_1 - Q_1'$