From *The Ascent of Man* by Jacob Bronowski

THE GRAIN IN THE STONE

In his hand
He took the golden Compasses, prepar'd
In Gods Eternal store, to circumscribe
This Universe. and all created things:
One foot he center'd, and the other turn'd
Round through the vast profunditie obscure,
And said, thus farr extend, thus farr thy bounds,
This be thy just Circumference, 0 World.

Milton, *Paradise Lost,* Book VII

John Milton described and William Blake drew the shaping of the earth in a single sweeping motion by the compasses of God. But that is an excessively static picture of the processes of nature. The earth has existed for more than four thousand million years. Through all this time, it has been shaped and changed by two kinds of action. The hidden forces within the earth have buckled the strata, and lifted and shifted the land masses. And on the surface, the erosion of snow and rain and storm, of stream and ocean, of sun and wind, have carved out a natural architecture.

Man has also become an architect of his environment, but he does not command forces as powerful as those of nature. His method has been selective and probing: an intellectual approach in which action depends on understanding. I have come to trace its history in the cultures of the New World which are younger than Europe and Asia. I centered my first essay on equatorial Africa, because that is where man began, and my second essay on the Near East, because that is where civilization began. Now it is time to remember that man reached other continents too in his long walk over the earth.

The Canyon de Chelly in Arizona is a breathless. secret valley, which has been inhabited by one Indian tribe after another almost without a break for two thousand years, since the birth of Christ; longer than any other place in North America. Sir Thomas Browne has a springing sentence: ‘The Huntsmen are up in America, and they are already past their first sleep in Persia.’ At the birth of Christ, the huntsmen were settling to agriculture in the Canyon de Chelly, and starting along the same steps in the ascent of man that had first been taken in the Fertile Crescent of the Middle East.

Why did civilization begin so much later in the New World than in the Old? Evidently because man was a latecomer to the New World. He came before boats were invented, which implies that he came dry-shod over the Bering Straits when they formed a broad land-bridge during the last Ice Age. The glaciological evidence points to two possible times when men might have wandered from the eastern most promontories of the Old World beyond Siberia to the rocky wastes of western Alaska in the New. One period was between 28,000 BC and 23,000 BC, and the other between14,000 BC and 10,000 BC. After that the flood of melt-water at the end of the last Ice Age raised the sea level again by several hundred feet and thereby turned the key on the inhabitants of the New World.

That means that man came from Asia to America not later than ten thousand years ago, and not earlier than about thirty thousand years ago. And he did not necessarily come all at once. There is evidence in archaeological finds (such as early sites and tools) that two separate streams of culture came to America. And, most telling to me, there is subtle but persuasive biological evidence that I can only interpret to mean that he came in two small, successive migrations.

The Indian tribes of North and South America do not contain all the blood groups that are found in populations elsewhere. A fascinating glimpse into their ancestry is opened by this unexpected biological quirk. For the blood groups are inherited in such a way that, over a whole population, they provide some genetic record of the past. The total absence of blood group A from a population implies, with virtual certainty, that there was no blood group A in its ancestor: and similarly, with blood group B. And this is in fact the state of affairs in America. The tribes of Central and South America (in the Amazon, for example, in the Andes, and in Tierra del Fuego) belong entirely to blood group O; so do some North American tribes. Others (among them the Sioux, the Chippewa, and the Pueblo Indians) consist of blood group O mixed with ten to fifteen per cent of blood group A. In summary, the evidence is that there is no blood group B anywhere in America, as there is in most other parts of the world.

In Central and South America, all the original Indian population is blood group O. In North America, it is of blood groups O and A. I can see no sensible way of interpreting that but to believe that a first migration of a small, related kinship group (all of blood group 0) came into America, multiplied, and spread right down to the south. Then a second migration, again of small groups, this time containing either A alone or both A and 0, followed them only as far as North America. The American Indians of the north, then, certainly contain some of this later migration and are, comparatively speaking, latecomers.

Agriculture in the Canyon de Chelly reflects this lateness. Although maize had long been cultivated in Central and South America, here it comes in only about the time of Christ. People are very simple, they have no houses, they live in caves. About AD 500 pottery is introduced Pit houses are dug in the caves themselves, and covered with a roof molded out of clay or adobe. And at that stage the Canyon is really fixed until about the year AD 1000, when the great Pueblo civilization comes in with stone masonry.

I am making a basic separation between architecture as molding and architecture as the assembly of parts. That seems a very simple distinction: the mud house, the stone masonry. But in fact, it represents a fundamental intellectual difference, not just a technical one. And I believe it to be one of the most important steps that man has taken, wherever and whenever he did so: the distinction between the molding action of the hand, and the splitting or analytic action of the hand.

It seems the most natural thing in the world to take some clay and mold it into a ball, a little clay figure, a cup, a pit house. At first, we feel that the shape of nature has been given us by this. But, of course, it has not. This is the man-made shape. What the pot does is to reflect the cupped hand; what the pit house does is to reflect the shaping action of man. And nothing has been discovered about nature herself when man imposes these warm, rounded, feminine, artistic shapes on her. The only thing that you reflect is the shape of your own hand.

But there is another action of the human hand which is different and opposite. That is the splitting of wood or stone; for by that action the hand (armed with a tool) probes and explores beneath the surface, and thereby becomes an instrument of discovery. There is a great intellectual step forward when man splits a piece of wood, or a piece of stone, and lays bare the print that nature had put there before he split it. The Pueblo people found that step in the red sandstone cliffs that rise a thousand feet over the Arizona settlements. The tabular strata were there for the cutting; and the blocks were laid in courses along the same bedding planes in which they had lain in the cliffs of the Canyon de Chelly.

From an early time, man-made tools by working the stone. Sometimes the stone had a natural grain, sometimes the toolmaker created the lines of cleavage by learning how to strike the stone. It may be that the idea comes, in the first place, from splitting wood, because wood is a material with a visible structure which opens easily along the grain, but which is hard to shear across the grain. And from that simple beginning man pries open the nature of things and uncovers the laws that the structure dictates and reveals. Now the hand no longer imposes itself on the shape of things. Instead, it becomes an instrument of discovery and pleasure together, in which the tool transcends its immediate use and enters into and reveals the qualities and the forms that lie hidden in the material. Like a man cutting a crystal, we find in the form within the secret laws of nature.

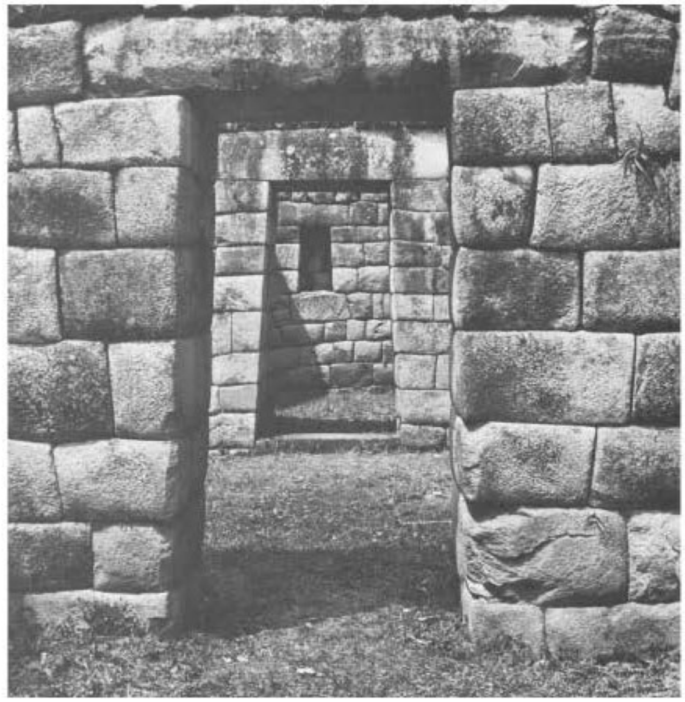
The notion of discovering an underlying order in matter is man's basic concept for exploring nature. The architecture of things reveals a structure below the surface, a hidden grain which, when it is laid bare, makes it possible to take natural formations apart and assemble them in new arrangements. For me this is the step in the ascent of man at which theoretical science begins. And it is as native to the way man conceives his own communities as it is to his conception of nature.

We human beings are joined in families, the families are joined in kinship groups, the kinship groups in clans, the clans in tribes, the tribes in nations. And that sense of hierarchy, of a pyramid in which layer is imposed on layer, runs through all the ways that we look at nature. The fundamental particles make nuclei, the nuclei join in atoms, the atoms join in molecules, the molecules join in bases, the bases direct the assembly of amino acids, the amino acids join in proteins. We find again in nature something which seems profoundly to correspond to the way in which our own social relations join us.

I am making a basic separation between architecture as molding and architecture as the assembly of parts. That seems a very simple distinction: the mud house, the stone masonry. But in fact, it represents a fundamental intellectual difference, not just a technical one. And I believe it to be one of the most important steps that man has taken, wherever and whenever he did so: the distinction between the molding action of the hand, and the splitting or analytic action of the hand. Stones make a wall, walls make a house, houses make streets, and streets make a city. A city is stones and a city is people; but it is not a heap of stones, and it is not just a jostle of people. In the step from the village to the city, a new community organization is built, based on the division of labor and on chains of command. The way to recapture that is to walk into the streets of a city that none of us has seen, in a culture that has vanished.

Machu Picchu is in the high Andes, eight thousand feet up in South America. It was built by the Incas at the height of their empire, round about AD 1500 or a little earlier (almost exactly when Columbus reached the West Indies) when the planning of a city was their greatest achievement. When the Spaniards conquered and plundered Peru in 1532, they somehow overlooked Machu Picchu and its sister cities. After that it was forgotten for four hundred years, until one winter's day in 1911. Hiram Bingham, a young archaeologist from Yale University, stumbled on it. By then it had been abandoned for centuries and was picked bare as a bone. But in that skeleton of a city lies the structure of every city civilization, in every age, everywhere in the world.

A city must live on a base, a hinterland, of a rich agricultural surplus; and the visible base for the Inca civilization was the cultivation of terraces. Of course, now the bare terraces grow nothing but grass, but once the potato was cultivated here (it is a native product of Peru), and maize which was long native by then, and in the first place had come from the north. And since this was a ceremonial city of some kind, when the Inca came to visit no doubt there were grown for him tropical luxuries of this climate like the coca, which is an intoxicating herb that only the Inca aristocracy was allowed to chew, and from which we derive cocaine.



The streets of a city that none of us has seen, in a culture that has vanished.

Mortar-less joints and cushioned faces of the granite blocks characterize Inca masonry.

At the heart of the terrace culture is a system of irrigation. This is what the pre-Inca empires and Inca empire made; it runs through these terraces, through canals and aqueducts, through the great ravines, down into the desert towards the Pacific and makes it flower. Exactly as in the Fertile Crescent it is the control of water that matters, so here in Peru the Inca civilization was built on the control of irrigation.

A large system of irrigation extending over an empire requires a strong central authority. It was so in Mesopotamia. It was so in Egypt. It was so in the empire of the Incas. And that means that this city and all the cities here rested on an invisible base of communication by which authority was able to be present and audible everywhere, directing orders from the center and information towards it. Three inventions sustained the network of authority: the roads, the bridges (in a wild country like this), the messages. They came to a center here when the Inca was here, and from him they went out of here. They are the three links by which every city is held to every other and which, we suddenly realize, are different in this city.

Roads, bridges, messages in a great empire are always advanced inventions, because if they are cut then authority is cut off and breaks down - in modem times they are typically the first target in a revolution.

We know that the Inca gave them much care. Yet on the roads there were no wheels, under the bridges there were no arches, the messages were not in writing. The culture of the Incas had not made these inventions by the year AD 1500. That is because civilization in America started several thousand years late, and was conquered before it had time to make all the inventions of the Old World.

It seems very strange that an architecture that moved large building stones on rollers could miss the use of the wheel; we forget that what is radical about the wheel is the fixed axle. It seems strange to make suspension bridges and miss the arch. And it seems strangest of all to have a civilization that kept careful records of numerical information, yet did not put them in writing - the Inca was as illiterate as his poorest citizen, or as the Spanish gangster who overthrew him.

The messages in the form of numerical data came to the Inca on pieces of string called *quipus*. The quipu only records numbers (as knots arranged like our decimal system) and I would dearly like to say, as a mathematician, that numbers are as informative and human a symbolism as words; but they are not. The numbers that described the life of a man in Peru were collected on a kind of punched card in reverse, a braille computer card laid out as a knotted piece of string. When he married, the piece of string was moved to another place in the kinship bundle. Everything that was stored in the Inca's armies, granaries and warehouses was noted on these quipus. The fact is that Peru was already the dreaded metropolis of the future, the memory store in which an empire lists the acts of every citizen, sustains him, assigns him his labors, and puts it all down impersonally as numbers.

It was a remarkably tight social structure. Everyone had a place; everyone was provided for; and everyone - peasant, craftsman or soldier - worked for one man, the supreme Inca. He was the civil head of state and he was also the religious incarnation of godhead. The artisans who lovingly carved a stone to represent the symbol of the link between the sun and its god and king. the Inca, worked for the Inca.

So, necessarily, it was an extraordinarily brittle empire. In less than a hundred years, from 1438 onwards, the Incas had conquered three thousand miles of coastline, almost everything between the Andes and the Pacific. And yet, in 1532 an almost illiterate Spanish adventurer, Francisco Pizarro, rode into Peru with no more than sixty-two terrible horses and a hundred and six foot soldiers; and overnight he conquered the great empire. How? By cutting the top off the pyramid - by capturing the Inca. And from that moment, the empire sagged, and the cities, the beautiful cities, lay bare for the gold plunderer and the vultures.

But, of course, a city is more than a central authority. What is a city? A city is people. A city is alive. It is a community which lives on a base of agriculture, so much richer than in a village, that it can afford to sustain every kind of craftsman and make him a specialist for a lifetime.

The specialists are gone, their work has been destroyed. The men who made Machu Picchu -the goldsmith, the coppersmith, the weaver, the potter - their work has been robbed. The woven fabric has decayed, the bronze has perished, the gold has been stolen. All that remains is the work of the masons, the beautiful craftsmanship of the men who made the city - for the men who make a city are not the Incas but the craftsmen. But naturally, if you work for an Inca (if you work for any one man) his tastes rule you and you make no invention. These men still worked to the end of the empire with the beam; they never invented the arch. Here is a measure of the time lag between the New World and the Old, because this is exactly the point which the Greeks reached two thousand years earlier, and at which they also stopped.

Paestum in Southern Italy was a Greek colony whose temples are older than the Parthenon: they date from about 500 BC. Its river has silted up and it is now separated from the sea by dull salt-flats. But its glory is still spectacular. Although it was ransacked by Saracen pirates in the ninth century, and by Crusaders in the eleventh, Paestum in ruins is one of the marvels of Greek architecture

Paestum is contemporary with the beginning of Greek mathematics; Pythagoras taught in exile in another Greek colony at Crotone not far from here. Like the mathematics of Peru two thousand years later, the Greek temples were bounded by the straight edge and the set square. The Greeks did not invent the arch either, and therefore their temples are crowded avenues of pillars. They seem open when we see them as ruins, but in fact they are monuments without spaces. That is because they had to be spanned by single beams, and the span that can be sustained by a flat beam is limited by the strength of the beam.

If we picture a beam lying across two columns, then a computer analysis will show the stresses in the beam increase as we move the columns farther apart. The longer the beam, the greater the compression that its weight produces in the top, and the greater the tension it produces in the bottom. And stone is weak in tension; the columns will not fail, because they are compressed, but the beam will fail when the tension becomes too great. It will fail at the bottom unless the columns are kept close together.

The Greeks could be ingenious in making the structure light, for example by using two tiers of columns. But such devices were only makeshifts; in any fundamental sense, the physical limitations of stone could not be overcome without a new invention. Since the Greeks were fascinated by geometry, it is puzzling that they did not conceive the arch. But the fact is that the arch is an engineering invention, and very properly is the discovery of a more practical and plebeian culture than either Greece or Peru.

The aqueduct at Segovia in Spain was built by the Romans about AD 100, in the reign of the emperor Trajan. It carries the waters of the Rio Frio that flows from the high Sierra ten miles away: The aqueduct spans the valley for almost half a mile in more than a hundred double-tiered round arches made of rough-hewn granite blocks, laid without lime or cement. Its colossal proportions so awed the Spanish and Moorish citizens in later and more superstitious ages that they named it El Puente del Diablo, the devil's bridge.

The circle remained the basis of the arch when it went into mass-production in Arab countries.

The Great Mosque at Cordoba.

The structure seems to us also prodigious and splendid out of proportion to its function of carrying water. But that is because we get water by turning a tap, and we lightly forget the universal problems of city civilizations. Every advanced culture that concentrates its skilled men in cities depends on the kind of invention and organization that the Roman aqueduct at Segovia expresses.

The Romans did not invent the arch in the first place in stone, but as a molded construction made of a kind of concrete. Structurally the arch is simply a method of spanning space which does not load the center more than the rest; the stress flows outward fairly equally throughout. But for this reason, the arch can be made of parts: of separate blocks of stone which the load compresses. In this sense, the arch is the triumph of the intellectual method which takes nature apart and puts the pieces together in new and more powerful combinations.

The Romans always made the arch as a semicircle; they had a mathematical form that worked well, and they were not inclined to experiment. The circle remained the basis of the arch still when it went into mass-production in Arab countries. This is plain in the cloistered, religious architecture that the Moors used; for instance, in the great mosque at Cordoba, also in Spain, built in AD 785 after the Arab conquest. It is a more spacious structure than the Greek temple at Paestum, and yet it has visibly run into similar difficulties; that is, once again it is filled with masonry, which cannot be got rid of without a new invention.

Theoretical discoveries that have radical consequences can usually be seen at once to be striking and original. But practical discoveries, even when they turn out to be far-reaching, often have a look that is more modest and less memorable. A structural innovation to break the limitation of the Roman arch did come, probably from outside Europe, and arrived almost by stealth at first. The invention is a new form of the arch based not on the circle, but on the oval. This does not seem a great change, and yet its effect on the articulation of buildings is spectacular. Of course, a pointed arch is higher, and therefore opens more space and light. But, much more radically, the thrust of the Gothic arch makes it possible to hold the space in a new way, as at Rheims. The load is taken off the walls, which can therefore be pierced with glass, and the total effect is to hang the building like a cage from the arched roof the inside of the building is open, because the skeleton is outside.

John Ruskin describes the effect of the Gothic arch admirably.

> *Egyptian and Greek buildings stand, for the most part, by their own weight and mass, one stone passively incumbent on another; but in the Gothic vaults and traceries there is a stiffness analogous to that of the bones of a limb, or fibers of a tree; an elastic tension and communication of force from part to part, and also a studious expression of this throughout every visible line of the building.*

Of all the monuments to human effrontery, there is none to match these towers of tracery and glass that burst into the light of Northern Europe before the year 1200. The construction of these huge, defiant monsters is a stunning achievement of human foresight - or rather, I ought to say; since they were built before any mathematician knew how to compute the forces in them, of human insight. Of course, it did not happen without mistakes and some sizeable failures. But what must strike the mathematician most about the Gothic cathedrals is how sound the insight in them was, how smoothly and rationally it progressed from the experience of one structure to the next.

The cathedrals were built by the common consent of townspeople, and for them by common masons. They bear almost no relation to the everyday, useful architecture of the time, and yet in them improvisation becomes invention at every moment. As a matter of mechanics, the design had turned the semicircular Roman arch into the high, pointed Gothic arch in such a way that the stress flows through the arch to the outside of the building. And then in the twelfth century also came the sudden revolutionary turning of that into the half arch: the flying buttress. The stress runs in the buttress as it runs in my arm when I raise my hand and push against the building as if to support it - there is no masonry where there is no stress. No basic principle of architecture was added to that realism until the invention of steel and reinforced concrete buildings.

One has the sense that the men who conceived these high buildings were intoxicated by their new-found command of the force in the stone. How else could they have proposed to build Vaults of 125 feet and 150 feet at a time when they could not calculate any of the stresses? Well, the vault of 150 feet - at Beauvais, less than a hundred miles from Rheims -collapsed. Sooner or later the builders were bound to run into some disaster: there is a physical limit to size, even in cathedrals. And when the roof of Beauvais collapsed in 1284, some years after it was finished, it sobered the high Gothic adventure: no structure as tall as this was attempted again. (Yet the empirical design may have been sound; probably the ground at Beauvais was simply not solid enough, and shifted under the building.) But the vault of 125 feet at Rheims held. And from 1250 onwards Rheims became a center for the arts of Europe.

The arch, the buttress, the dome (which is a sort of arch in rotation) are not the last steps in bending the grain in nature to our own use. But what lies beyond must have a finer grain: we now have to look for the limits in the material itself. It is as if architecture shifts its focus at the same time as physics does, to the microscopic level of matter. ln effect, the modern problem is no longer to design a structure from the materials, but to design the materials for a structure.

The masons carried in their heads a stock, not so much of patterns as of ideas, that grew by experience as they went from one site to the next. They also carried with them a kit of light tools. They marked out with compasses the oval shapes for the vaults and the circles for the rose windows. They defined their intersections with calipers, to line them up and fit them into repeatable patterns. Vertical and horizontal were related by the T-square, as they had been in Greek mathematics, using the right angle. That is, the vertical was fixed with the plumb-line, and the horizontal was fixed, not with a spirit-level, but with a plumb-line joined to a right angle.

The wandering builders were an intellectual aristocracy (like the watchmakers five hundred years later) and could move all over Europe, sure of a job and a welcome; they called themselves freemasons as early as the fourteenth century. The skill that they carried in their hands and their heads seemed to others to be as much a mystery as a tradition, a secret fund of knowledge that stood outside the dreary formalism of pulpit learning that the universities taught. When the work of the freemasons petered out, by the seventeenth century, they began to admit honorary members, who liked to believe that their craft went back to the pyramids. That was not really a flattering legend, because the pyramids were built with a much more primitive geometry than the cathedrals

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Masons at work, 13th century

Yet there is something in the geometrical vision which is universal. Let me explain my preoccupation with beautiful architectural sites - such as the cathedral at Rheims. What does architecture have to do with science? Particularly, what does it have to do with science the way we used to understand it at the beginning of this century, when science was all numbers - the coefficient of expansion of this metal, the frequency of that oscillator?

The fact of the matter is that our conception of science now, towards the end of the twentieth century, has changed radically. Now we see science as a description and explanation of the underlying structures of nature; and words like structure, pattern, plan, arrangement, architecture constantly occur in every description that we try to make. I have by chance lived with this all my life, and it gives me a special pleasure: the kind of mathematics I have done since childhood is geometrical. However, it is no longer a matter of personal or professional taste, for now that is the everyday language of scientific explanation. We talk about the way crystals are put together, the way atoms are made of their parts - above all we talk about the way that living molecules are made of their parts. The spiral structure of DNA has become the most vivid image of science in the last years. And that imagery lives in these arches.

What did the people do who made this building and others like it? They took a dead heap of stones, which is not a cathedral, and they turned it into a cathedral by exploiting the natural forces of gravity, the way the stone is laid naturally in its bedding planes, the brilliant invention of the flying buttress and arch and so on. And they created a structure that grew out of the analysis of nature into this superb synthesis. The kind of man who is interested in the architecture of nature today is the kind of man who made this architecture nearly eight hundred years ago. There is one gift above all others that makes man unique among the animals, and it is the gift displayed everywhere here: his immense pleasure in exercising and pushing forward his own skill.

A popular cliché in philosophy says that science is pure analysis or reductionism, like taking the rainbow to pieces; and art is pure synthesis, putting the rainbow together. This is not so. All imagination begins by analyzing nature. Michelangelo said that vividly, by implication, in his sculpture (it is particularly clear in the sculptures that he did not finish), and he also said it explicitly in his sonnets on the act of creation

When that which is divine in us doth try
To shape a face, both brain and hand unite
To give, from a mere model frail and slight,
Life to the stone by Art's free energy.

'Brain and hand unite': the material asserts itself through the hand, and thereby prefigures the shape of the work for the brain. The sculptor, as much as the mason, feels for the form within nature, and for him it is already laid down there. That principle is constant.

The best of artists hath no thought to show
Which the rough stone in its superfluous shell
Doth not include: to break the marble spell
Is all the hand that serves the brain can do.

By the time Michelangelo carved the head of Brutus, other men quarried the marble for him. But Michelangelo had begun as one of the quarrymen in Carrara, and he still felt that the hammer in their hands and in his was groping in the stone for a shape that was already there.

The quarrymen work in Carrara now for the modern sculptors who come here - Marino Marini, Jacques Lipchitz and Henry Moore. Their descriptions of their work are not as poetic as Michelangelo's, but they carry the same feeling. The reflections of Henry Moore are particularly apposite as they run back to the first genius of Carrara.

> *To begin with, as a young sculptor, I could not afford expensive stone, and I got my stone by going round the stone-yards and finding what they would call a 'random block'. Then I had to think in the same way that Michelangelo might have done, so that one had to wait until an idea came that fitted the shape of the stone and that was seen, the idea, in that block.*

Of course, it cannot be literally true that what the sculptor imagines and carves out is already there, hidden in the block. And yet the metaphor tells the truth about the relation of discovery that exists between man and nature; and it is characteristic that philosophers of science (Leibniz in particular) have turned to the same metaphor of the mind prompted by a vein in the marble. In one sense, everything that we discover is already there: a sculptured figure and the laws of nature are both concealed in the raw material. And in another sense, what a man discovers is discovered *by him;* it would not take exactly the same form in the hands of someone else - neither the sculptured figure nor the law of nature would come out in identical copies when produced by two different minds in two different ages. Discovery is a double relation of analysis and synthesis together. As an analysis, it probes for what is there; but then, as a synthesis, it puts the parts together in a form by which the creative mind transcends the bare limits, the bare skeleton, that nature provides.

Sculpture is a sensuous art. (The Eskimos make small sculptures that are not even meant to be seen, only handled.) So, it must seem strange that I choose as my model for science, which is usually thought of as an abstract and cold enterprise, the warm, physical actions of sculpture and architecture. And yet it is right. We have to understand that the world can only be grasped by action, not by contemplation. The hand is more important than the eye. We are not one of those resigned, contemplative civilizations of the Far East or the Middle Ages, that believed that the world has only to be seen and thought about - and who practiced no science in the form that is characteristic for us. We are active; and indeed, we know, as something more than a symbolic accident in the evolution of man, that it is the hand that drives the subsequent evolution of the brain. We find tools today made by man before he became man. Benjamin Franklin in 1778 called man ‘a tool-making animal’, and that is right.

I have described the hand when it uses a tool as an instrument of discovery; it is the theme of this essay. We see this every time a child learns to couple hand and tool together - to lace its shoes, to thread a needle, to fly a kite or to play a penny whistle. With the practical action there goes another, namely finding pleasure in the action for its own sake - in the skill that one perfects, and perfects by being pleased with it. This at bottom is responsible for every work of art, and science too: our poetic delight in what human beings do because they can do it. The most exciting thing about that is that the poetic use in the end has the truly profound results. Even in prehistory man already made tools that have an edge finer than they need have. The finer edge in its turn gave the tool a finer use, a practical refinement and extension to processes for which the tool had not been designed.

Henry Moore calls his sculpture *The Knife Edge.* The hand is the cutting edge of the mind. Civilization is not a collection of finished artefacts, it is the elaboration of processes. In the end, the march of man is the refinement of the hand in action.

The most powerful drive in the ascent of man is his pleasure in his own skill. He loves to do what he does well and, having done it well, he loves to do it better. You see it in his science. You see it in the magnificence with which he carves and builds, the loving care, the gaiety, the effrontery. The monuments are supposed to commemorate kings and religions, heroes, dogmas, but in the end the man they commemorate is the builder.

So, the great temple architecture of every civilization expresses the identification of the individual with the human species. To call it ancestor worship, as in China, is too narrow. The point is that the monument speaks for the dead man to the living, and thereby establishes a sense of permanence which is a characteristically human view: the concept that human life forms a continuity which transcends and flows through the individual. The man buried on his horse or revered in his ship at Sutton Hoo becomes, in the stone monuments of later ages, a spokesman for their belief that there is such an entity as mankind, of which we are each a representative - in life and death.

I could not end this essay without turning to my favorite monuments, built by a man who had no more scientific equipment than a Gothic mason. These are the Watts Towers in Los Angeles. built by an Italian called Simon Rodia. He came from Italy to the United States at the age of twelve. And then at the age of forty-two, having worked as a tile-setter and general repairman, he suddenly decided to build, in his back garden tremendous structures out of chicken wire, bits of railway tie, steel rods, cement, sea shells, bats of broken glass, and tile of course - anything that he could find or that the neighborhood children could bring him. It took him thirty-three years to build them He never had anyone to help him because, he said. 'most of the time I didn't know what to do myself'. He finished them in 1954; he was seventy-five by then. He gave the house, the garden and the towers to a neighbor, and simply walked out.

‘I had in mind to do something big.’ Simon Rodia had said, ‘and I did. You have to be good or bad to be remembered.’ He had learned his engineering skill as he went along, by doing, and by taking pleasure in the doing. Of course, the City Building Department decided that the towers were unsafe, and in 1959 they ran a test on them. They tried to pull down one of the towers. I am happy to say that they failed. So, the Watts Towers have survived, the work of Simon Rodia's hands, a monument in the twentieth century to take us back to the simple, happy, and fundamental skill from which all our knowledge of the laws of mechanics grows.

The tool that extends the human hand is also an instrument of vision. It reveals the structure of things and makes it possible to put them together in new, imaginative combinations. But of course, the visible is not the only structure in the world. There is a liner structure below. And the next step in the ascent of man is to discover a tool to open up the invisible structure of matter.