POVERTIES AND TRIUMPHS OF THE CHINESE SCIENTIFIC TRADITION

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The historical civilization of China is, with the Indian and the European-Semitic, one of the three greatest in the world, yet only in recent years has any enquiry been begun into its contributions to science and technology. Apart from the great ideas and systems of the Greeks, between the first and the fifteenth centuries the Chinese, who experienced no "dark ages," were generally much in advance of Europe; and not until the scientific revolution of the late Renaissance did Europe draw rapidly ahead. Before that time, however, the West had been profoundly affected not only in its technical processes but in its very social structures and changes by discoveries and inventions emanating from China and East Asia. Not only the three which Lord Bacon listed (printing, gunpowder and the magnetic compass) but a hundred others—mechanical clockwork, the casting of iron, stirrups and efficient horse-harness, the Cardan suspension and the Pascal triangle, segmental-arch bridges and pound-locks on canals, the stern-post rudder, fore-and-aft sailing, quantitative cartography—all had their effects, sometimes earth-shaking effects, upon a Europe more socially unstable.

Why, then, did modern science, as opposed to ancient and medieval science (with all that modern science implied in terms of political dominance), develop only in the Western world? Nothing but a careful analysis, a veritable titration, of the cultures of East and West will eventually answer this question. Doubtless many factors of an intellectual and philosophical character played their part, but there were certainly also important social and economic causes which demand investigation.

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In what follows an attempt will be made to describe some of the elements of strength and weakness in the growth and development of the indigenous Chinese tradition of science and invention, in contrast with that of Europe.

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Both East and West had strengths and weaknesses now well discernible as we

look back along the course which man's knowledge of nature and control of nature took in the diverse regions of the Old World.

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First of all it is essential to define the differences between ancient and medieval science on the one hand, and modern science on the other. I make an important distinction between the two. When we say that modern science developed only in Western Europe at the time of Galileo in the late Renaissance, we mean surely that there and then alone there developed the fundamental bases of the structure of the natural sciences as we have them today, namely the application of mathematical hypotheses to Nature, the full understanding and use of the experimental method, the distinction between primary and secondary qualities, the geometrisation of space, and the acceptance of the mechanical model of reality. Hypotheses of primitive or medieval type distinguish themselves quite clearly from those of modern type. Their intrinsic and essential vagueness always made them incapable of proof or disproof, and they were prone to combine in fanciful systems of gnostic correlation. In so far as numerical figures entered into them, numbers were manipulated in forms of "numerology" or number-mysticism constructed *a priori*, not employed as the stuff of quantitative measurements compared *a postiori*. We know the primitive and medieval Western scientific theories, the four Aristotelian elements, the four Galenical humours, the doctrines of pneumatic physiology and pathology, the sympathies and antipathies of Alexandrian proto-chemistry, the *tria prima* of the alchemists, and the natural philosophies of the Kabbala. We tend to know less well the corresponding theories of other civilizations, for instance the Chinese theory of the two fundamental forces Yin and Yang, or that of the five elements, or the elaborate system of the symbolic correlations. In the West Leonardo da Vinci, with all his brilliant inventive genius, still inhabited this world; Galileo broke through its walls. This is why it has been said that Chinese science and technology remained until late times essentially Vincian, and that the Galilean break-through occurred only in the West. That is the first of our starting-points.

Until it had been universalized by its fusion with mathematics, natural science could not be the common property of all mankind. The sciences of the medieval world were tied closely to the ethnic environments in which they had arisen, and it was very difficult, if not impossible, for the people of those different cultures to find any common basis of discourse. That did not mean that inventions of profound sociological importance could not diffuse freely from one civilization to another—mostly in fact from east to west. But the mutual incomprehensibility of the ethnically-bound concept systems did severely restrict possible contacts and transmissions in the realm of scientific ideas. This is why technological elements spread widely through the length and breadth of the Old World, while scientific elements for the most part failed to do so.

Nevertheless the different civilizations did have scientific interchanges of great importance. It is surely quite clear by now that in the history of science and technology the Old World must be thought of as a whole. Even Africa may have been within its circuit. But when this oecumenical view is taken, a great paradox presents itself. Why did modern science, the mathematization of hypotheses about Nature, with all its implications for advanced technology, take its meteoric rise *only* in the West at the time of Galileo? This is the most obvious question which many have asked but few have answered. Yet there is another which is of quite equal importance. Why was it that between the second century B.C. and the sixteenth century A.D. East Asian culture was much *more* efficient than the European West in applying human knowledge of Nature to useful purposes? Only an analysis of the social and economic structures of Eastern and Western cultures, not forgetting the great role of systems of ideas, will in the end suggest an explanation of both these things.

The Face of Science and Technology in Traditional China

Before the river of Chinese science flowed, like all other such rivers, into this sea of modern science, there had been remarkable achievements in mathematics. Decimal place-value and a blank space for the zero had begun in the land of the Yellow River earlier than anywhere else, and decimal metrology had gone along with it. By the first century B.C. Chinese artisans were checking their work with sliding calipers decimally graduated. Chinese mathematical thought was always profoundly algebraic, not geometrical, and in the Sung and the Yuan (twelfth to fourteenth centuries A.D.) the Chinese school led the world in the solution of equations, so that the triangle called by Pascal's name was already old in China in A.D. 1300. We often find examples of this sort; the system of linked and pivoted rings which we know as the Cardan suspension was commonly used in China a thousand years before Cardan's time. As for astronomy, I need only say that the Chinese were the most persistent and accurate observers of celestial phenomena anywhere before the Renaissance. Although geometrical planetary theory did not develop among them they conceived an enlightened cosmology, mapped the heavens using our modern co-ordinates, and kept records of eclipses, comets, novae and meteors still useful, for example to the radio-astronomers, today. A brilliant development of astronomical instruments also occurred, including the invention of the equatorial mounting and the clock-drive; and this development was in close dependence upon the contemporary capabilities of the Chinese engineers. Their skill affected also other sciences such as seismology, for it was a Chinese man of science, Chang Hêng, who built the first practical seismograph about A.D.130.

Three branches of physics were particularly well developed in ancient and medieval China—optics, acoustics and magnetism. This was in striking contrast with the West where mechanics and dynamics were relatively advanced but magnetic phenomena almost unknown. Yet China and Europe differed most profoundly perhaps in the great debate between continuity and discontinuity, for just as Chinese mathematics was always algebraic rather than geometrical, so

Chinese physics was faithful to a prototypic wave theory and perennially averse to atoms. One can even trace such contrasts in preferences in the field of engineering, for whenever an engineer in classical China could mount a wheel horizontally he would do so, while our forefathers preferred vertical mountings—water-mills and wind-mills are typical examples.

A pattern which we very often find in comparing China's achievements with those of Europe is that while the Chinese of the Chou, Chhin and Han, contemporary with the Greeks, did not rise to such heights as they, nevertheless in later centuries there was nothing in China which corresponded to the period of the Dark Ages in Europe. This shows itself rather markedly in the sciences of geography and cartography. Although the Chinese knew of discoidal cosmographic world-maps, they were never dominated by them. Quantitative cartography began in China with Chang Hêng and Phei Hsiu about the time when Ptolemy's work was falling into oblivion, indeed soon after his death, but it continued steadily with a consistent use of the rectangular grid right down to the coming of the Jesuits in the seventeenth century A.D. The Chinese were also very early in the field with advanced survey methods and the making of relief maps. In the geological sciences and in meteorology the same pattern presents itself.

Mechanical engineering and indeed engineering in general was a field in which classical Chinese culture scored special triumphs. Both the forms of efficient harness for equine animals—a problem of linkwork—originated in the Chinese culture-area, and there also water-power was first used for industry about the same time as in the West (first century A.D.); not, however, so much for grinding cereals as for the operation of metallurgical bellows. The development of iron and steel technology in China constitutes a veritable epic, with the mastery of iron-casting some fifteen centuries before its achievement in Europe. Contrary to the usual ideas, mechanical clockwork began not in early Renaissance Europe but in Thang China, in spite of the highly agrarian character of East Asian civilization. Civil engineering also shows many extraordinary achievements, notably iron-chain suspension bridges and the first of all segmental arch structures, the magnificent bridge built by Li Chhun in A.D. 610. Hydraulic engineering was always prominent in China on account of the necessity of control of waterways for river conservation (defence against flood and drought), irrigation, and tax-grain transport.

In martial technology the Chinese also showed notable inventiveness. The first appearance of gunpowder occurs among them in the ninth century A.D., and from A.D. 1000 onwards there was a vigorous development of explosive weapons some three centuries before they appeared in Europe. Probably the key invention was that of the fire-lance at the beginning of the twelfth century A.D., in which a rocket composition enclosed in a bamboo tube was used as a close-combat weapon. From this derived, I have little doubt, all subsequent barrel guns and cannon of whatever material constructed. Other aspects of technology also have their importance, especially that of silk in which the Chinese excelled so early. Here the mastery of a textile fibre of extremely long staple appears to have led to the first development of technical devices so important as the driving-belt and the chain-drive. It is also possible to show that the first appearance of the standard method of converting rotary to longitudinal motion is found in connexion with later forms of the metallurgical blowing-engine referred to above. I must pass over other well-known inventions such as the development of paper, block-printing and movable-type printing, or the astonishing story of porcelain.

There was no backwardness in the biological fields, either, and here we find many agricultural inventions arising from an early time. As in other subjects, we have texts which parallel those of the Romans such as Varro and Columella from a similar period. If space permitted, one could take examples from plant protection which would include the earliest known use of the biological control of insect pests. Medicine is a field which aroused the interests of the Chinese in all ages, and which was developed by their special genius along lines perhaps more different from those of Europe than in any other case. I think that I can do no more here than refer simply to one remarkable fact, namely that the Chinese were free from the prejudice against mineral remedies which was so striking in the West; they needed no Paracelsus to awaken them from their Galenical slumbers for in these they had never participated. They were also the greatest pioneers of the techniques of inoculation.

Contrasts between China and the West

Let us come now to the further examination of some of the great contrasts to which I have already referred. In the first place it can be shown in great detail that the *philosophia perennis* of China was an organic materialism. This can be illustrated from the pronouncements of philosophers and scientific thinkers of every epoch. The mechanical view of the world simply did not develop in Chinese thought, and the organicist view in which every phenomenon was connected with every other according to hierarchical order was universal among Chinese thinkers. Nevertheless this did not prevent the appearance of great scientific inventions such as the seismograph, to which we have already referred. In some respects this philosophy of Nature may even have helped. It was not so strange or surprising that the lodestone should point to the pole if one was already convinced that there was an organic pattern in the cosmos. If, as is truly the case, the Chinese were worrying about the magnetic declination before Europeans even knew of the polarity, that was perhaps because they were untroubled by the idea that for action to occur it was necessary for one discrete object to have an impact upon another; in other words, they were inclined *a priori* to field theories, and this predilection may very well also account for the fact that they arrived so early at a correct conception of the cause of sea tides. One may find remarkable statements, as early as the San Kuo period, of action at a distance taking place without any physical contact across vast distances of space.

Again, as we have said, Chinese mathematical thought and practice was in-

variably algebraic, not geometrical. No Euclidean geometry spontaneously developed among them, and this was doubtless inhibitory for the advances they were able to make in optics, where however, incidentally, they were never handicapped by the rather absurd Greek idea that rays were sent forth by the eye. Euclidean geometry was probably brought to China in the Yuan (Mongol) period but did not take root until the arrival of the Jesuits. Nevertheless all this did not prevent the successful realization of great engineering inventions—we have mentioned two already, the most useful method of interconversion of rotary and rectilinear motion by means of eccentric, connecting-rod and piston-rod; and the successful achievement of the oldest form of mechanical clock. What this involved was the invention of an escapement, namely a mechanical means of slowing down the revolution of a set of wheels so that it would keep time with humanity's primary clock, the apparent diurnal revolution of the heavens. In this connexion it is interesting to find that Chinese practice was not, as might at first sight be supposed, purely empirical. The successful erection of the great clock-tower of Su Sung at Khaifêng in A.D. 1088 was preceded by the elaboration of a special theoretical treatise by his assistant Han Kung-Lien, which worked out the trains of gears and general mechanism from first principles. Something of the same kind had been done on the occasion of the first invention of this kind of clock by I-Hsing and Liang Ling-Tsan early in the eighth century A.D., six centuries before the first European mechanical clocks with their verge-and-foliot escapements. Moreover, though China had no Euclid, that did not prevent the Chinese from developing and consistently employing the astronomical coordinates which have completely conquered modern astronomy and are universally used today, nor did it prevent their consequent elaboration of the equatorial mounting, although there was nothing but a sighting-tube, and as yet no telescope, to put in it.

Thirdly, there is the wave-particle antithesis. The prototypic wave theory with which the Chinese concerned themselves from the Chhin and Han onwards was connected with the eternal rise and fall of the two basic natural principles, the Yang and Yin. From the second century A.D. onwards atomistic theories were introduced to China time after time, especially by means of the Buddhist contacts with India, but they never took any root in Chinese scientific culture. All the same this lack of particulate theory did not prevent the Chinese from curious achievements such as the recognition of the hexagonal system of snowflake crystals many centuries before this was noticed in the West. Nor did it hinder them from helping to lay the foundation of knowledge of chemical affinity, as was done in some of the alchemical tractates of the Thang, Sung and Yuan. There the absence of particulate conceptions was probably less inhibitory than it otherwise might have been, because it was only after all in the post-Renaissance period in Europe that these theories became so fundamental for the rise of modern chemistry.

I should not want to disagree altogether with the idea that the Chinese were a fundamentally practical people, inclined to distrust all theories. One must beware, however, of carrying this too far, because the Neo-Confucian school in the eleventh, twelfth and thirteenth centuries A.D. achieved a wonderful philosophical synthesis strangely parallel in time with the scholastic synthesis of Europe. One might also say that the disinclination of the Chinese to engage in theory, especially geometrical theory, brought advantages with it. For example, Chinese astronomers did not reason about the heavens like Eudoxus or Ptolemy but they did avoid the conception of crystalline celestial spheres which dominated medieval Europe. By a strange paradox, when Matteo Ricci came to China at the end of the sixteenth century A.D. he mentioned in one of his letters a number of the foolish ideas entertained by the Chinese, among which prominently figured the fact that "they do not believe in crystalline celestial spheres"; it was not long before the Europeans did not either. Moreover, this fundamental practicality did not imply an easily satisfied mind. Very careful experimentation was practised in classical Chinese culture. For example the discovery of magnetic declination would not have occurred unless the geomancers had been attending most carefully to the positions of their needles, and the triumphs of the ceramics industry could never have been achieved without fairly accurate temperature measurement and the means of repetition at will of oxidizing or reducing conditions within the kilns. The fact that relatively little written material concerning these technical details has come down to us springs from social factors which prevented the publication of the records which the higher artisans certainly kept. Enough remains, either by title, like the *Mu Ching* (Timberwork Manual) which we shall speak of again, or in MS. form, like the Fukien shipwrights' manual, to show that this literature existed.

The Old World Origins of the New Science

Now I should like to return to the question raised at the beginning, and go a little further into the distinction between modern science on the one hand, and ancient and medieval science on the other. I shall thus have to deal somewhat more fully with certain points that have already been touched upon. As the contributions of the Asian civilizations are progressively uncovered by research, an opposing tendency seeks to preserve European uniqueness by exalting unduly the role of the Greeks and claiming that not only modern science, but science as such, was characteristic of Europe, and of Europe only, from the very beginning. For these thinkers the application of Euclidean deductive geometry to the explanation of planetary motion in the Ptolemaic system constituted already the marrow of science, which the Renaissance did no more than propagate. The counterpart of this is a determined effort to show that all scientific developments in non-European civilizations were really nothing but technology.

For example, our most learned medievalist has recently written:

> Impressive as are the technological achievements of ancient Babylonia, Assyria, and Egypt, of ancient China and India, as scholars have presented them to us they lack the essential elements of science, the generalized conceptions of scientific explanation and of mathematical proof. It seems to me that it was the Greeks who invented natural science as we know it, by their assumption of a permanent, uniform, abstract order and laws by means of which the regular changes observed in the world could be explained by deduction, and by their brilliant idea of the generalized use of scientific theory tailored according to the principles of non-contradiction and the empirical test. It is this essential Greek idea of scientific explanation, "Euclidean" in logical form, that has introduced the main problems of scientific method and philosophy of science with which the Western scientific tradition has been concerned.[1]

Again in a recent interesting and stimulating survey entitled *Science since Babylon* we read:

> What is the origin of the peculiarly scientific basis of our own high civilization? . . . Of all limited areas, by far the most highly developed, most recognizably modern, yet most continuous province of scientific learning, was mathematical astronomy. This is the mainstream that leads through the work of Galileo and Kepler, through the gravitation theory of Newton, directly to the labours of Einstein and all mathematical physicists past and present. In comparison, all other parts of modern science appear derivative or subsequent; either they drew their inspiration directly from the successful sufficiency of mathematical and logical explanation for astronomy, or they developed later, probably as a result of such inspiration in adjacent subjects. . . . Our civilization has produced not merely a high intellectual grasp of science but also a high scientific technology. By this is meant something distinct from the background noise of the low technology that all civilizations and societies have evolved as part of their daily life. The various crafts of the primitive industrial chemists, of the metallurgists, of the medical men, of the agriculturists—all these might become highly developed without presaging a scientific or industrial revolution such as we have experienced in the past three or four centuries.[2]

Even the distinguished and enlightened author of *Science in History* writes (in correspondence):

> The chief weakness of Chinese science lay precisely in the field which most interested them, namely astronomy, because they never developed the Greek geometry, and perhaps even more important, the Greek geometrical way of seeing things which provided the Renaissance with its main intellectual weapon for the breakthrough. Instead they had only the extremely precise recurrence methods deriving from Babylonian astronomy, and these, on account of their exactitude, gave them a fictitious feeling of understanding astronomical phenomena.[3]

Finally the author of a noted book, *The Edge of Objectivity*, says:

> Albert Einstein once remarked that there is no difficulty in understanding why China or India did not create science. The problem is rather why Europe did, for science is a most arduous and unlikely undertaking. The answer lies in

Greece. Ultimately science derives from the legacy of Greek philosophy. The Egyptians, it is true, developed surveying techniques and conducted certain surgical operations with notable finesse. The Babylonians disposed of numerical devices of great ingenuity for predicting the patterns of the planets. But no Oriental civilization graduated beyond technique or thaumaturgy to curiosity about things in general. Of all the triumphs of the speculative genius of Greece, the most unexpected, the most truly novel, was precisely its rational conception of the cosmos as an orderly whole working by laws discoverable in thought. . . . [4]

The statement of Einstein here referred to is contained in a now famous letter which he sent to J. E. Switzer of San Mateo, California, in 1953. It runs:

Dear Sir,

The development of Western science has been based on two great achievements, the invention of the formal logical system (in Euclidean geometry) by the Greek philosophers, and the discovery of the possibility of finding out causal relationships by systematic experiment (at the Renaissance). In my opinion one need not be astonished that the Chinese sages did not make these steps. The astonishing thing is that these discoveries were made at all.

Sincerely yours,
Albert Einstein.

It is very regrettable that this Shavian epistle with all its lightness of touch is now being pressed into service to belittle the scientific achievements of the non-European civilizations. Einstein himself would have been the first to admit that he knew almost nothing concrete about the development of the sciences in the Chinese, Sanskrit and Arabic cultures except that *modern* science did not develop in them, and his great reputation should not be brought forward as a witness in this court. I find myself in complete disagreement with all these valuations and it is necessary to explain briefly why.

First, these definitions of mathematics are far too narrow. It would of course be impossible to deny that one of the most fundamental elements in Galileo's thinking was the geometrical study of kinematic problems. Again and again he praises the power of geometry as opposed to "logic." And geometry remained the primary tool for studying the problems of physical motion down to the early nineteenth century. But vast though the significance of deductive geometry was, its proofs never exhausted the power of the mathematical art. Although we speak of the Hindu-Arabic numerals, the Chinese were in fact the first, as early as the fourteenth century B.C., to be able to express any desired number, however large, with no more than nine signs. Chinese mathematics, developing the earlier Babylonian tradition, was always, as I have already said, overwhelmingly arithmetical and algebraical, generating such concepts and devices as those of decimal place-value, decimal fractions and decimal metrology, negative numbers, indeterminate analysis, the method of finite differences, and the solution of higher numerical equations. Very accurate values of π were early computed. The Han

mathematicians anticipated Horner's method for obtaining the roots of higher powers. The triangle of binomial coefficients, as we have seen, was already considered old in the *Ssu Yuan Yü Chien* of A.D. 1303. Indeed in the thirteenth and fourteenth centuries A.D. the Chinese algebraists were in the forefront of advance as their Arabic counterparts had been in previous centuries, and so also the Indian mathematicians when they originated trigonometry (as we know it) nearly a thousand years earlier. To say that whatever algebra was needed by Vieta and by Newton they could easily have invented themselves may be uncritical genius-worship, but it is worse, it is unhistorical, for the influence of Asian ways of computation on European mathematicians of the later Middle Ages and the Renaissance is well established. And when the transmissions are examined the balance shows that between 250 B.C. and A.D. 1250, in spite of all China's isolations and inhibitions, a great deal more mathematical influence came out of that culture than went in.

Moreover the astronomical application of Euclidean geometry in the Ptolemaic system was not all pure gain. Apart from the fact (which some of these writers unaccountably seem to forget) that the resulting synthesis was in fact objectively wrong, it ushered the Western medieval world into the prison of the solid crystalline celestial spheres—a cosmology incomparably more naïve and *borné* than the infinite empty spaces of the Chinese *hun-thien* school or the relativistic Buddhist philosophers. It is in fact important to realize that Chinese thought on the world and its history was over and over again more boldly imaginative than that of Europe. The basic principles of Huttonian geology were stated by Shen Kua in the late eleventh century A.D., but this was only a counterpart of a Plutonian theme recurring since the fourth century A.D., that of the *sang thien* or mountains which had once been at the bottom of the sea. Indeed the idea of an evolutionary process, involving social as well as biological change, was commonly entertained by Chinese philosophers and scientifically interested scholars, even though sometimes thought of in terms of a succession of world renewals following the catastrophes and dissolutions assumed in the recurrent *mahākalpas* of Indian speculation. One can see a striking echo of this open-mindedness in the calculations made by I-Hsing about A.D. 724 concerning the date of the last general conjunction. He made it come out to 96,961,740 years before—rather a different scale from "4004 B.C. at six o'clock in the evening."

Thirdly, the implied definitions of science are also much too narrow. It is true that mechanics was the pioneer among the modern sciences, the "mechanistic" paradigm which all the other sciences sought to imitate, and emphasis on Greek deductive geometry as its base is so far justifiable. But that is not the same thing as saying that geometrical kinematics is all that science is. Modern science itself has not remained within these Cartesian bounds, for field theory in physics and organic conceptions in biology have deeply modified the earlier mechanistic world-picture. Here knowledge of magnetic phenomena was all-important, and this was a typically Chinese gift to Europe. Although we do not know the way-stations through which it came, its priority of time is such as to place the burden of proof on those who would wish to believe in an independent discovery. The fact is that science has many aspects other than geometrical theorizing. To begin with, it is nonsense to say that the assumption of a permanent, uniform, abstract order and laws by means of which the regular changes in the world could be explained, was a purely Greek invention. The order of Nature was for the ancient Chinese the *Tao*, and as a *chhang Tao* it was an "unvarying Way." "Every natural phenomenon," says the fourth-century B.C. *Chi Ni Tzu* book, "the product of Yin and Yang, has its fixed compositions and motions with regard to other things in the network of Nature's relationships." "Look at things," wrote Shao Yung in the eleventh century A.D., "from the point of view of things, and you will see their true nature; look at things from your own point of view, and you will see only your own feelings; for nature is neutral and clear, while feelings are prejudiced and dark." The organic pattern in Nature was for the medieval Chinese the *Li*, and it was mirrored in every subordinate whole as one or another *wu li* of particular things and processes. Since the thought of the Chinese was in all ages profoundly organic and impersonal they did not envisage laws of a celestial law-giver—but nor did the Greeks, for it is easily possible to show that the full conception of Laws of Nature attained definitive status only at the Renaissance.

What the Chinese did do was to classify natural phenomena, to develop scientific instruments of great refinement for their respective ages, to observe and record with a persistence hardly paralleled elsewhere, and if they failed (like all medieval men, Europeans included) to apply hypotheses of modern type, they experimented century after century obtaining results which they could repeat at will. When one recites this list of the forms of scientific activity it becomes difficult to see how anyone could deny them their status as essential components of fully developed world science, biological and chemical as well as astronomical and physical, if it was not in the interest of some instinctive *parti pris*.

Elaborating, *kho hsüeh*, the traditional and current Chinese term for science, means "classification knowledge." The first star catalogues, probably pre-Hipparchan, open its story in China. It is then exemplified in the long series of rational pharmacopœias which begins with the second-century B.C. *Shen Nung Pên Tshao*. It helped to lay the basis of our knowledge of chemical affinity in the theories of polarities (*i*) and categories (*lei*) found in treatises such as the fifth-century A.D. *Tshan Thung Chhi Wu Hsiang Lei Pi Yao*. If systematic classifications of parhelic phenomena in the heavens (*Chin Shu*), and of the diseases of men and animals on earth (*Chu Shih Ping Yuan*), were worked out a full thousand years before Scheiner and Sydenham, this was only the expression of the firm hold which the Chinese had on this basic form of scientific activity. Perhaps the view of science which I am criticizing rests partially on too great a preoccupation with astronomy, and too little with biology, mineralogy and chemistry.

Then as to apparatus. That the Hellenistic Greeks were capable of producing highly complicated scientific instruments is shown by the anti-Kythera computing machine, but this is a very rare, indeed a unique example. It would be fairer to admit that throughout the first fifteen centuries of our era Chinese instrument-making was generally ahead, and (as in such instances as the seismograph and the mechanical clock) often much ahead, of anything that Europe could show.

Actually the invention of clockwork was directly connected with the very absence of planetary models in Chinese thinking, for while on ecliptic co-ordinates no real body ever moves, declination circles are tracks of true motion, and the equatorial-polar system was a direct invitation to construct planetaria mechanically rotated. So, too, modern positional astronomy employs not the ecliptic co-ordinates of the Greeks but the equatorial ones of the Chinese. Nor need we confine ourselves to the astronomical sciences here, for a wealth of advanced techniques is to be found in those alchemical treatises of which the *Tao Tsang* is full.

Surely, again, observation, accurate and untiring, is one of the foundation-stones of science. What records from an antique culture are of vital interest to radio-astronomers today? Nothing from Greece, only the nova, comet and meteor lists of China's star-clerks. They it was who first established (by the seventh century A.D. at least) the constant rule (*chhang tsê*) that the tails of comets point away from the sun. Renaissance astronomers who quarrelled so much among themselves about the priority of the study of sun-spots might have been somewhat abashed if they had known that these had been observed since the first century B.C. in China, and not only observed but recorded in documents reliably handed down. When Kepler penned his New Year letter on the hexagonal form of snowflake crystals in A.D. 1611 he did not know that his contemporary Hsieh Tsai-Hang was puzzling over just the same thing, not, however, as a new idea but as a fact which had been known and discussed since the original discovery reported by Han Ying in the second century B.C. When we look for the original root of the cloud-seeding process in the comparison of snow-flake crystals with those of various salts and minerals, we find it not in the eighteenth-century A.D. experiments of Wilcke but in the acute observation of Chu Hsi in the twelfth century A.D. Thus it will surely be apparent that if God could geometrize so could the Tao, and the Europeans were not the only men who could trace its operations in forms both living and non-living. Finally if an example is needed from the biological sciences, let us remember the brilliant empirical discovery of deficiency diseases clearly stated by the physician Hu Ssu-Hui in the fourteenth century A.D.

Degree of accuracy in observation is also relevant. Indeed it is a vital feature, for it springs from that preoccupation with quantitative measurement which is one of the most essential hallmarks of true science. The old astronomical lists gave stellar positions in measured degrees, of course, the hydraulic engineers were recording precisely the silt-content of rivers in the first century B.C., and the pharmacists early developed their systems of dosages, but another example, less known, is more striking. Of the dial-and-pointer readings which make up so much of modern science, a search throughout the medieval world between the eighth and the fourteenth centuries A.D. would reveal instruments capable of giving them only in China. I refer to the needles of the magnetic compasses used first by geomancers, then (at least a century before Europe) by the sea-captains. Now it is a remarkable fact (as we have seen) that the Chinese were worrying about the cause of magnetic declination for a considerable time before Europeans knew even of magnetic directivity. Indeed the geomantic compass in its final form embodies two additional rings of points, one staggered 7½° east and the other 7½° west—these represent the remains of observations of declination, eastwards before about A.D. 1000 and westwards thereafter. We have reason to believe that this disturbing discovery was first made some time in the ninth or tenth centuries A.D., and it could never have been made if the observers had not been marking with extraordinary accuracy—and honesty—the "true path" of the needle. It is even legitimate to compare this feat in principle with the discovery of the inert or noble gases so long afterwards by Rayleigh and Ramsay, residual bubbles which others had put down to experimental error or simply neglected. The honesty deserves emphasis also, for it was not shown so clearly when Europeans came up against the same phenomenon four or five centuries later. Or one might say that they had a greater tolerance of error, being content with "there or thereabouts." The history of magnetic declination in the West has been obscured by the fact that the compass-makers "fiddled" the instrument by fixing a card askew to make it read right, and little or nothing was written about the matter till the sixteenth century A.D. Similarly, Robert Norman used to "fiddle" his compasses to make the needles lie horizontally, until one day he lost his temper and really looked into the trouble, so rediscovering "dip" or inclination.

Perhaps the greatest objection to the attempt of the Hellenizers to save European superiority is the fact that the Greeks were not really experimenters. Controlled experimentation is surely the greatest methodological discovery of the scientific revolution of the Renaissance, and it has never been convincingly shown that any earlier group of Westerners fully understood it. I do not propose to claim this honour for the medieval Chinese either, but they came just as near it theoretically, and in practice often went beyond European achievements. Although the ceramics technologists of China undoubtedly paid great attention to their temperatures and to the oxidizing-reducing atmospheres of their kilns, I shall not return to this here, for the Hellenizers would no doubt include the immortal products of the Sung potters in that "background noise of low technology" which was all that non-European cultures could attain. I prefer, then, to take other examples: Tu Wan's labelling of fossil brachiopods ("stone swallows") to demonstrate that if they ever flew through the air it was only to drop down by process of weathering, or the long succession of pharmaceutical experiments on animals carried out by the alchemists from Ko Hung to Chhen Chih-Hsü, or the many trials made by the acoustics experts on the resonance phenomena of bells and strings, or the systematic strength-of-material tests which internal evidence shows must have been undertaken before the long beam bridges across the Fukienese estuaries could have been constructed. Is it possible to believe that apparatus so complex as that of the water-wheel linkwork escapement clocks, or indeed much of the textile machinery, could ever have been devised without long periods of workshop experimentation? The fact that written records of it have not come down to us is only what we should expect in a medieval literary culture. The fact that none of it was carried out on isolated and simplified objects, such as balls rolling down inclined planes, is again only what was characteristic of pre-Renaissance practice everywhere.

I do not say that the Greek *praeparatio evangelica* was not an essential part of the background of modern science. What I do want to say is that modern exact and natural science is something much greater and wider than Euclidean geometry and Ptolemaic mathematical astronomy; more rivers than those have emptied into its sea. For anyone who is a mathematician and a physicist, perhaps a Cartesian, this may not be welcome; but I myself am professionally a biologist and a chemist, more than half a Baconian, and I therefore do *not* think that what constituted the spearhead of the Galilean break-through constitutes the whole of science. What happened to crystallize the mathematization of experimental hypotheses when the social conditions were favourable does not exhaust the essence. If mechanics was the primary science, it was *primus inter pares*. If physics celestial and terrestrial has the battle-honours of the Renaissance, it is not to be confused with the whole army of science, which has many brave regiments besides.

"The spearhead, but not the whole, of science." In pondering over a better way of representing the situation, it occurred to me that we ought perhaps to make a clearer distinction between factors which were concerned in the direct historical genesis of modern science, and factors which fell into place later after the Galilean break-through. We shall also have to distinguish more clearly between science and technology. Suppose we erect a classification of four pigeonholes, science vertically on the left and technology vertically on the right, and let the upper boxes represent direct historical genesis while the lower ones represent subsequent reinforcement. Then taking the upper left-hand compartment first, the contribution of the Greeks will have the greatest share, for Euclidean deductive geometry and Ptolemaic astronomy, with all that they imply, were undoubtedly the largest factor in the birth of the "new, or experimental, science"—in so far as any antecedents played a part at all, for we must not undervalue its basic originality. In spite of Ptolemy and Archimedes, the occidental ancients did not, as a whole, experiment. But Asian contributions will not be absent from this compartment, for not only must we leave a place for algebra and the basic numerational and computational techniques, we must not forget the significance of magnetism, and knowledge of this realm of phenomena had been built up exclusively in the Chinese culture-area, which thus powerfully influenced Europe through Gilbert and Kepler. Here one remembers also the adoption of the Chinese equatorial co-ordinates by Tycho. But the Greeks predominate. In the upper right-hand compartment the situation is entirely different, for in technology Asian influences in and before the Renaissance (especially Chinese) were legion—I need mention only the efficient horse-harnesses, the technology of iron and steel, the inventions of gunpowder and paper, the escapement of the mechanical clock, and basic engineering devices such as the driving-belt, the chain-drive, and the standard method of converting rotary to rectilinear motion, together with nautical techniques such as the leeboard and the stern-post rudder. Alexandria also ran.

The lower compartments will now be available to take achievements of the Asian cultures which, though not genetically connected with the first rise of modern science yet deserve all praise; they may or may not be directly genetically related to their corresponding developments in post-Renaissance modern science. A case of direct influence could be found in the Chinese doctrine of infinite empty space instead of solid crystalline celestial spheres, but it did not operate until after Galileo's time. Cases of later incorporation would be the development of undulatory theory in eighteenth-century A.D. physics, which immensely elaborated characteristically Chinese ideas without directly building on them, or the use of ancient and medieval Chinese records by radio-astronomers. So also, if atomism, not mathematics, proved to be the soul of chemistry, which found itself so much later than physics, this elaborated Indian and Arabic ideas of great subtlety without knowingly basing itself thereon. A good case of the absence of any influence would be the seismograph as used in China from the second to the seventh centuries A.D.; though an outstanding achievement, it was almost certainly unknown to any of the scientific men who developed seismographs in post-Renaissance Europe. Chinese biological and pathological classification systems occupy the same position; they were clearly unknown to Linnaeus and Sydenham, but none the less worthy of study, for only by drawing up the balance-sheet in full shall we ever ascertain what each civilization contributed to human advancement. It is not legitimate to require of every scientific or technological activity that it should have contributed to the advancement of the European culture-area. What happened in other civilizations is entirely worth studying for its own sake. Must the history of science be written solely in terms of one continuous thread of linked influences? Is there not an ideal history of human thought and knowledge of nature, in which every effort can find its place, irrespective of what influences it received or handed on? Modern universal science and the history and philosophy of universal science will embrace all in the end.

It only remains to consider the contents of the right-hand lower compartment. Here we have to think of technical inventions which only became incorporated, whether or not by re-invention, into the corpus of modern technology after the Renaissance period. A case in point might be the paddle-wheel boat, but it is uncertain, for we do not know whether the first European successes were based on a Byzantine idea never executed, or on a vast fund of practical Chinese achievement during the preceding millennium. A better case would be the differential gear, for though present in the south-pointing carriage of ancient China, it must almost certainly have arisen again independently in Europe. So also the Chinese methods of steel-making by the co-fusion process and by the direct oxygenation of cast iron, though of great seniority to the siderurgy of Europe, were not able to exert any influence upon it, if indeed they did, which is still uncertain, until long after the Renaissance. Similarly it might be unwise to connect too closely the crucible steel of Huntsman with that of the age-old Indian wootz process.

In all this I have tried to offer an *opinio conciliatrix* in friendly fashion to those who may have been shocked by the objective attitude which I always seek to adopt in weighing European claims. If we think out the matter as I suggest, we may feel greater need for recognizing several kinds of values; the value of that which helped directly to effect the Galilean break-through, the value of that

which became incorporated in modern science later on, and last but not least, the value of that residue which yet renders other civilizations no less worthy of study and admiration than Europe.

The erroneous perspective which I am criticizing can be seen particularly well in the use of the possessive plural personal pronoun. Some Western historians of science constantly speak of "*our* modern culture" and "*our* high civilization" (I italicize). *The Edge of Objectivity* reveals even more clearly the mood in which they approach the comparative study of men's efforts to understand and control the natural world.

> Anxious though our moments are, today is not the final test of wisdom among statesmen or virtue among peoples. The hard trial will begin when the instruments of power created by the West come fully into the hands of men not of the West, formed in cultures and religions which leave them quite devoid of the Western sense of some ultimate responsibility to man in history. The secular legacy of Christianity still restrains our world in some slight measure, however self-righteous it may have become on one side and however vestigial on the other. Men of other traditions can and do appropriate *our* science and technology, but not our history or values. And what will the day hold when China wields the bomb? And Egypt? Will Aurora light a rosy-fingered dawn out of the East? Or Nemesis?

This is certainly very near the edge. It would induce in the reader a lamentable and unworthy attitude of mind in which fear would jostle its counterpart, possessiveness. Surely it would be better to admit that men of the Asian cultures also helped to lay the foundations of mathematics and all the sciences in their medieval forms, and hence to set the stage for the decisive break-through which came about in the favourable social and economic milieu of the Renaissance. Surely it would be better to give more attention to the history and values of these non-European civilizations, in actual fact no less exalted and inspiring than our own. Then let us give up that intellectual pride which boasts that "we are the people, and wisdom was born with us." Let us take pride enough in the undeniable historical fact that *modern* science was born in Europe and only in Europe, but let us not claim thereby a perpetual patent thereon. For what was born in the time of Galileo was a universal palladium, the salutary enlightenment of all men without distinction of race, colour, faith or homeland, wherein all can qualify and all participate. Modern universal science, yes; Western science, no!

N O T E S

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