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Towards a Science of Science

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TOWARDS A SCIENCE OF SCIENCE *

I. ON THE DEFINITION OF A SCIENCE OF SCIENCE

1. The Tao Te Ching, the great classic which sets out the Chinese way of understanding the operation of nature and of society, begins with an explicit warning of the sterilising effect of too rigid a definition:

The Way that may truly be regarded as the Way is other than a permanent Way.
The terms that may truly be regarded as terms are other than permanent terms.

(Duyvendak's translation)

The Way is one never-ending change in an organic system. We will not, therefore, rigorously define either science or the science of science, since they are both activities of this nature. We may take Price's definition as a general indication of field: by science of science we intend "the history, philosophy, sociology, psychology, economics, political science and operations research (*etc.*) of science, technology, medicine (*etc.*)". This blanket statement covers the programme of work formulated by the Ossowskis in 1936 [1] (and recently [2] reprinted). They used the term for the first time in the sense in which we wish to use it now, but attributed the original coinage about 1927 to Prof. Kotarbiński.

2. To begin with, we must stress the reflexive nature of the science of science. (We tolerate the jingle in the name because it does this). The repetition emphasises that we must attempt a synthesis, as demanded by physics, psychology, religion, *etc.* of subject and object, observer and observed, creator and created, particle and wave, focus and field — each pair of terms becoming a single organic system. Science must examine itself.

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The significance of Newton's apple was that it made the heavens and the earth a single system. Quantum mechanics achieved its advance by including the effect of the hitherto detached observer on the system observed. The Sufis and other mystics proclaimed union with God and so on. Andrew Lang has parodied the all-embracing, Brahma of Indian philosophy:

I am the batsman and the bat,
I am the bowler and the ball,
The umpire, the pavilion cat,
The roller, pitch and stumps and all.

3. As in other sciences, the science of science might be arbitrarily divided into pure and applied branches. The first, descriptive and analytic, asks "how do science and the scientist work?" and the second, normative and synthetic, asks "how can science be applied to the needs of human society?". The science of science must be a proper science, perhaps with special characteristics. There must be observation, speculation and experiment or operational research. Just as a consideration of the flight of an arrow no longer provides sufficient data for deducing the laws of physics as they are today, so a limited, armchair experience of how science works is not sufficient for constructing a science of science. Philosophers discredit themselves by still treating "time" in Zeno's terms, while disregarding recent ideas on relativity, quantum mechanics and astrophysics. The science of science is not to be spun out of the air but has to be laboriously dug for or sought in the market place.

II. THE DEMAND FOR A SCIENCE OF SCIENCE

1. In 1599 Edward Wright (dedication to *Certain Errors of Navigation*) exhorted his patron to further scientific enquiry on the grounds that "even God himself apparently seemeth to aim at this mark; for else what should it mean that within these few score years Hee hath discovered to the world the greatest and rarest secrets, farre exceeding all that could be found out by the wit and industries of man in divers thousands of years before".

Paraphrased by Thomas Kuhn, Wright believed that a radical change in the paradigm of scientific discovery had taken place. That most interesting figure, Simon Sturtevant, saw it too and tried to analyse the new modes of discovery.

Bacon too, of course, at about the same time, wanted to know how the new paradigm worked and listed (*Advancement of Learning,* book 9) "A recapitulation of the deficiencies of knowledge... to be supplied by posterity". They included: "The Art of inventing Arts", "The Art of Indication or Direction in Philosophy", and again in the *Novum Orga-*

num (Book 1, aphorism 11): "As the present sciences are useless for the discovery of effects, so the present system of logic is useless for the discovery of the sciences".

Perceptive people at the time of the scientific revolution noticed that something new was happening and asked what it was.

2. In recent decades there are signs of another change of paradigm. Price's measurements have demonstrated the exponential increase in the quantity of science (or scientific publication) since 1660 and have shown that the trends observed cannot continue unchanged much longer [3]. In 1965 the USA will spend 3.2% of its GPN, some 21 milliard dollars, on research and development and this figure had been increasing at 13% *p.a.* over the last 13 years (doubling time 5.6 years) [4].

Even in 1905 Henry Adams, the American historian, noticed this and wrote:

"The assumption of unity which was the mark of human thought in the middle-ages has yielded very slowly to the proofs of complexity. The stupor of science before radium is a proof of it. Yet it is quite sure, according to my score of ratios and curves, that, at the accelerated rate of progression shown since 1600, it will not need another century or half century to tip thought upside down. Law, in that case, would disappear as theory or *a priori* principle, and give place to force. Morality would become police. Explosives would reach cosmic violence. Disintegration would overcome integration" [5].

Adams, however, was a historian who realised that quantitative methods were needed in attacking history. His science of history, to be sure, consisted of scientific images and metaphors (as he recognised himself) rather than serious demonstrations but it was immensely suggestive.

In consequence of the acceleration of change every man's life must be less and less like that of this father. More and more problems will be encountered for which there is no traditional solution. The problem-solving role of science therefore becomes of increasing importance and we need to know how all aspects of science work.

The mere quantitative change in certain factors brings qualitatively different problems. Just as we begin to discern a pattern in the development of science it changes a further escalation.

3. The demand for a science of science is partly on the general intellectual level — *rerum cognoscere causas* — but it is mainly created by the following practical factors:

a) The impending curtailment of the exponentially increasing amount spent on research and development in the USA. The Federal Government's contribution has been doubling every four years recently and clearly this acceleration cannot continue very long. In the USA as well as in poorer countries some choice must be made between expensive research and development projects. Criteria for such choices are needed. Rational schemes for the education and employment of scientists have to be devised.

b) Production potential seems to increase as a high power of the money spent on research and economic and scientific disparities between countries have increased in spite of improved communications and general interdepedence.

c) There are signs of sickness in science — the Pyramid-building syndrome, we might call it — and not only in the USA. With the proliferation of atomic energy commissions the signs of consumption are conspicuous. R and D of military hardware is the form which Dreadnaught-building now takes and the effects on science and scientists require examination.

d) The results of science in providing food, subsistence and physical and intellectual adventure have been so striking that there is a popular demand for the better application of the evident potentialities. The development of a strategy, on a world scale, for the employment of resources is the ultimate aim of the applied science of science.

III. PRE-CONDITIONS FOR A SCIENCE OF SCIENCE

We suggest that sufficient pre-conditions for the science of science now obtain and that it is for the first time possible to begin to have a coherent body of knowledge, theory and technique in this field. Some of these conditions are:

1. Contemporary science now has a sufficient volume and variety to enable valid statistical examinations to be made. Head-counting at the time of Kepler and Galileo would have been largely meaningless.

2. We now have a corpus of case history from the past sufficient to enable us to recognise the principal phenomena and to classify them.

3. Science is now being pursued and studied in a wide variety of cultural milieux. The particular qualities of science arising from the special factors of the Graeco-Jewish-Christian-Roman traditions of Western Europe can thus be separated from the more general factors by comparison with, for example, Chinese, Islamic, Hindu, Japanese or Russian experiences. Economic factors can also perhaps be identified by comparing science in different economic systems.

4. There are now possibilities of making conscious experiments in the organisation and environment of science.

5. The tempo of life, due mostly to better communications, is now so great that experiments formerly impossible can now be conducted. Indeed most of the above factors owe much to communications but this may be slightly disadvantageous in that the observation of science pro-

ceeding in isolation from world influences is difficult. It is now hard to find a culture uncontaminated by spores and fall-out from the general world atmosphere.

6. We are in an exciting stage of science itself in which new connections and syntheses are rapidly emerging. The outlines of the hierarchic and spatially and temporarily interconnected structure of the whole edifice of culture can be imagined. We begin to see how new properties begin to appear at each level of complexity.

Price's work on the fabric of scientific communication is a pioneering attempt to analyse this quantitavely and marks the beginning of the disclosure of the laws of motion of science [6].

IV. THE CHARACTER OF A SCIENCE OF SCIENCE

1a) We consider that in this science, as in most others, it is not possible to predict, *a priori*, what the theoretical framework of the science will look like, leaving experiment and observation merely to paint in the details. Having a theoretical framework, however, is not deleterious but essential, since it will accentuate the distinguishability of details which do not fit in and which will require the framework to be modified. Observations which do fit in will receive added meaning from their location in a framework.

b) Different civilizations had different frameworks. In Europe, there was once a definite Aristotelian or dogmatic religious picture of the universe. Contradictions demanded resolution (by argument or experiment). In India, on the other hand, a prodigy could be observed but the reaction might only be: "It is just a miracle — so what?" — no contradiction being felt. In China again, a proto-scientist regarded himself as directly coupled into the working of nature and felt that he was himself not working properly when nature was out of balance and *vice versa*.

c) We expect that in the study of science as a phenomenon new types of concept will emerge. For example, in the study of language, another essentially human, organic, system like science itself, new kinds of statistics and mathematics are painfully developing. The communication theory and the linguistic statistics associated with Weaver, Shannon, Brillouin, Wiener, Herdan and others have brought new attitudes both to language and to physics (it was perhaps begun by M. Müller in 1861 [7].

d) In the last two decades, biology has, using concepts developed through work in X-ray diffraction and with the electron microscope, changed before our eyes. It now has a far more satisfactory and definite conceptual framework than before, and has become a real science and not just a mass of observations. This is due to the identification of hierarchies of complexity atomic, molecular, polymeric, structural, cellular, organismic, communal *etc.*, each level only being understood in terms of the levels immediately above and below it.

e) Science is what scientists do, so that individual psychology and behaviour is a basic level for the science of science. Unfortunately psychology is more difficult than molecular biology and although it began to become a science with the appearance in 1860 of *Elemente der Psychophysik* by G. T. Fechner, it has moved rather slowly.

Other social sciences such as economics are in a largely pre-scientific state in spite of the obvious possibilities of quantisation.

f) Although we would like to see Galton's maxim "whenever you can, count" applied to the science of science, a warning against spurious quantisation might be entered. (Blackett's law: Any project takes 3.14 times as long to finish as you thought it would — parodies this apparent accuracy). Price has drawn attention to Lotka's Law (1926) on "The frequency distribution of scientific productivity." Much more of Lotka's book *The Elements of Physical Biology* [8] foreshadows systems analysis and is very suggestive for the science of science. It is most salutory to compare this, and for example, D'Arcy Thompson's book *Growth and Form*, with contemporary molecular biology. We see at once that a little direct observation of fine mechanism is worth a great deal of blind analysis of macroscopic consequences.

It is clear too that at the level above the science of science — the behaviour of human societies, science is hardly beginning. Any theory dealing with the large scale features of science must include the effects of military, space-race and prestige pressures, for example. L. R. Richardson after examining the difficult physical question of the weather in *Weather Prediction by Numerical Processes* (1922), turned to the still more difficult psycho-social question of war [9]. So far, such studies have been without much effect.

At present, at the beginning of the science of science, science studied as a phenomenon must, like any other subject of study, be attacked where we can get a foothold and where it is most likely to yield.

2. We can identify the following kinds of study.

a) S t a t i s t i c a l a t t a c k s. Such studies disclose laws or regularities and we look for the kind of mechanisms which may give rise to them in the way that monomolecular, bimolecular and chain reactions are identified from rates of reaction. It is difficult, however, to say much about detailed mechanisms from the behaviour of a few macroscopic parameters.

The argument for planning is really that in a phase-incoherent system intensities add, while in a planned system it is the amplitudes which add. The difference is that between the laser and the candle or between a random walk and a planned walk. However, to make a laser we need to understand the detailed mechanism and statistics is perhaps not the best way of doing this.

Sources of data assembled for other purposes can be exploited but desiderata for the collection of data should be formulated. Any model of scientific organisation of the Leontief or Stone input/output matrix type [10], will require the collection of special information (for example, on the migration of scientists).

b) Detailed study of critical cases. This, of course, is the fundamental work of the orthodox historian of science, and needs little elaboration. We could perhaps instance the particular cases of simultaneous discovery as being specially informative. Or, turning the situation round we may ask: "Of two men working on the same problem, why did one and not the other find the answer?" Like Price, we can quote Matthew (24,42) "Then shall be two men working in a field, one is taken and one is left" — why? This is a parallel to the use of identical twins in agricultural research — a technique giving more information than sophisticated and costly factor analysis.

c) Systems research. This might be called the physiology of science and consists in making models of various parts or properties of scientific activity. Like group theory, systems analysis can study isomorphous systems with quite different components. Physiology also implies the examination or dissection of scientific systems to show their structures. For example the information in the book *50 Years of X-ray Diffraction* [11] can be laid out to show master — pupil — scholl sequences and interconnections and cases of one discovery leading to another, like the fabric of the blood vessels of a frog.

d) Experimental approaches. With very large organisations now managing scientific research experiments can be done on science as a system. Measurements can be made in complex economic or other structures by disturbing part with a signal of a special form and recovering the same waveform out of the "noise" of the total displacement at a given place. This is like deducting the contents of an n-terminal black box from external measurements. The experiments can be non-destructive and may even pass unrecognised as experiments.

Mission directed research is, in terms of expenditure, the commonest mode of working but, since the human brain is very slow but can handle many problems at once, being backed by a remarkable memory system, it may not even be the best way for accomplishing missions.

One might speculate that if the main economic problem of India is the vulnerability of the traditional export products, it might be better to have all Indian scientists thinking part of the time about the problems, rather than a few specialists thinking all the time.

There must be modes of conducting research which have not yet been tried.

e) Classification is the stage which normally follows the collection of case histories. We now have enough for them to be classified in some such system as the following (indeed we think Merton has done so); for example

α) due to one man stimulated by a chance observation which supplied a vital clue,

β) due to two men each in possession of parts of the situation — "sub-critical assemblies" (Crick and Watson perhaps),

γ) due to a team systematically looking in all possible places for an expected answer, *etc.*

The time, the place and the girl and some further spark of enthusiasm are all necessary for the act of creation. Questions of application at once arise:

If it is characteristic of each fertile scientist that he carries round a thousand questions to which he would like answers, how can fruitful interactions be arranged to occur with optimum frequency? Is it worthwhile for an institution to have a Socratic figure (or court jester) who goes round asking silly questions?

A central problem of all scientific work is "how are two heads better than one"? — But even more difficult is "how does even one head work" [12].

V. TO SUMMARISE

To promote a science of science we should encourage:

1. The study of contemporary science as it happens

a) by getting academic posts for the science of science.

b) by getting established departments of the history of science to deal with the contemporary scene — we suspect that in British Universities there are no Departments of science as such — only specialised departments. It is today nobody's job to look at science as a whole. (Manchester University begins such a course in Oct. 1966).

c) by supporting the profession and activity of science critic — making it comparable to that of literary critic but giving duties of condensation and critical review.

d) by getting governmental bodies to collect statistics in proper form and to set up their own units for the study of science. This is needed, of course, also on an international scale, for science is a world-wide activity.

2. Experimental work in the science of science, such as:

a) Comparisons of various methods of training for science.

b) Sociological experiments — provision of the right environment for science.

c) Psycho-social experiments on creativity — "brain-storming", "nonsense groups" *etc.*

d) Studies of the economics of science.

e) Seeing if a small community making optimum use of science could be established. The Sheikh of Kuwait might be persuaded to follow the example of Harun al Rashid and become a lavish patron of education and science.

3. Orthodox history of science.

a) tendencies towards a more synoptic view, with factor analyses, classification of case histories and identification of paradigms of discovery might be encouraged,

b) and also field work in non-European cultures (where written records were sometimes of lower importance than master pupil relationships),

c) and, less seriously (perhaps as a recreation and as a therapy for historians tired by too much work in libraries) a "Society for Primitive Technology" or "Promethean Club" which could run week-end camps where scientists and others would actually try various early techniques as A. G. Drachman does in his own Greek workshop. Recording of surviving techniques before they disappear is already actively pursued in many places but not perhaps in enough.

d) In general we would like to see science simply take its place as a part of our universal culture contributing to the physical and intellectual development of all.

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