Great shifts in scientific thinking and human development in the last four hundred years: Evolution and impact of western science

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P. J. Bowles who published in 1992 the first time an integrated history of all branches of science dealing with different aspects of our natural environment from geology and geochemistry up to biology and ecology, remarked in the preface that the subject of investigation had to be treated in relation to „the changing attitude of western civilization to the environment ... Science often seems part of the problem: its professional fragmentation symbolizes the materialistic trend in modern thought, the desire to divide nature up into separate units, each of which can be studied in isolation and exploited for short-term profit“. By the end of the 20th century, Bowles saw not only philosophical or epistemological but mainly practical reasons „for reintroducing a sense of the unity of Nature“ that would persuade scientists „to rethink their tendency to compartmentalize everything“. The historical survey should „encourage the hope that a new, more responsible science of the environment is not ruled out by the very nature of science itself“.

Bowles' statement meets the core of the subject: science – as the most important and effective means to explore the global problems of human existence and to recommend reasonable ways to overcome these problems – is at the same time part of the problems it is challenged to solve. This may be seen as an external, visible expression of an invisible, deep-rooted duality that characterizes modern science as a kind of human activity. In epistemological terms, apart from ethical implications, we might describe it as the opposition of analytical and synthetic attitudes. Of course, modern science is a powerful means of synthesis as well as of analysis, and history of science exhibits many magnificent synthetic theories, from Newton's Mechanics to Einstein's General Relativity. Nevertheless, there is no symmetry between analytical and synthetic aspects in scientific progress. Usually, the analytical attitude, the more and more sophisticated compartmentalization of reality is dominating. Before a great theoretical synthesis – in a scientific and not speculative manner – can succeed, a lot of data has to be produced, and the production of data is mainly connected with active intervention into nature, and so is (only to a much larger extent) application of scientific results for practical aims. Surely, the relation between theoretical synthesis and data production is a reciprocal one, strong theories open new possibilities for exploring nature, but nevertheless main emphasis is put upon data production that always tends to exceed available theoretical frameworks and thus to keep scientific progress in move. The predominantly analytical attitude of science, connected with a cultural and social background that regards nature as a subject to be controlled by man and to be exploited for human purposes, may explain the (at least partial) responsibility of modern science for contemporary global risks and uncertainties.

Perhaps the most striking feature of modern science is its irresistible growth, corresponding to the endless economic growth that is widely regarded as an irreplaceable presupposition of good and worthy life for all the inhabitants of our planet and that nevertheless generates, to an always increasing extent, large social disparities. Incessantly grows the amount of knowledge available to science, and ever growing – on average, not necessarily everywhere and at all times – are also the input, the extent, and the output of scientific activities. Most of the features connected with modern science have become social mass phenomena – the number of students and scientists, the number of universities and research institutes, the number of journals, papers, citations, co-citations and so on – resulting in a field of statistics in which the individual seems to dissolve. Together with the volume of scientific achievements, because of the ambivalence of science the field of social risks is expanding and acquiring new qualities, too. During the Thirties, the well-known British crystallographer J. D. Bernal – deeply alarmed about the impact of the Great Depression on science as well as about the growing interaction between science and military on the eve of World War II – developed the idea that such a powerful agent like modern science had to be deliberately controlled by human society with the special assistance of socially responsible scientists and that it therefore would be necessary to create a „science of science“ using the means of science to investigate science itself with all its benefits and dangers. More precisely, Bernal was the highly talented spokesman of a broad movement among contemporary scientists rather than the single creator of the new subject, but he was the author of the first comprehensive monograph about this field – a classical book, regrettably deprived of its well-deserved effect due to the war. 25 years later, in honour of Bernal and his work, M. Goldsmith and A. Mackay including an anniversary article by Bernal himself; Bernal stressed the necessity of a responsible research strategy based on a science of science, and he characterized the science of science as the truly sensational scientific innovation in the second half of the 20th century. The science of science project was ethically and politically connoted and led to the institutionalisation of science policy studies.

But generally spoken, the final result was rather disappointing. In the decades of confrontation and competition between East and West, science of science flourished under both competing political systems, meanwhile the collapse of Soviet Union and her satellites was accompanied by a marked decline of interest and engagement in science research – a puzzling fact on the background of the general conviction that we were entering „information society“ or „knowledge society“ usually associated with the idea of growing social impact and social esteem of science. It cannot be denied that Bernal's forecast had failed – provided, he had really understood it as a forecast of things to come. But it seems to me more presumable that he had meant it as a requirement addressed to society in general and especially to the world-wide community of scientists. Then we must admit, more than 50 years after *The Social Function of Science*, that Bernal's urgent desideratum has been inexcusably underestimated and neglected, inside the scientific community as well as in recent science policy.

The very fact that scientific knowledge is always in progress – although the growth patterns for various indicators and in various fields of science are very different – can be seen as a kind of fundamental constant in a period of human history that is rather characterized by a lack of great and inspiring ideas for the future of mankind and by a diffuse, but wide-spread feeling of insecurity and uncertainty about the possible consequences of globalisation.

In its most advanced sections, the production of scientific knowledge has already reached rhythm and stability similar to the technological regime of an automatic factory – impressively illustrated by the breathtaking velocity of decoding human DNA sequences in the Human Genome Project. During the 19^{th} century, the solid pace of scientific progress was mainly perceived as a non-problematic value, as a guarantee for an enlightened future in peace, justice, and wealth. Socialist movements often regarded science as their natural ally; it was a commonplace to connect progress in living nature taken for granted by the Darwinian theory with progressive shifts in human society, brought about by scientifically instructed steady evolution or even by a radical revolutionary overthrow of existing political and economic structures. Even the increasing destruction capacity of modern weapons as a consequence of science-based armament was included into the general picture of optimism. A. Nobel who destined one category of the famous prize taken from his legacy especially for peace activities was firmly convinced that the development of more and more terrible weapons would deter possible aggressors and thus secure stable peace (an argument permanently used – but without Nobel's candid faith – to justify arms race during the whole 20th century). Yet after World War II, when scientists were fully aware of the terrible effects of chemical, biological, and nuclear weapons and organized influential movements for peace, disarmament , and total stop or at least strict control of military R & D, the general conviction was that after having banned the abuse of science for warfare the free and ever increasing employment of science for civil purposes would guarantee for a future in happiness and abundance of material and intellectual goods for all people. The „peaceful atom", working restlessly in power stations all over the earth, should produce such an abundance of energy for everybody that former inequalities in the distribution of wealth would become nearly meaningless; this was a usual commitment hold even by critical scientists.

We had to read the first reports to the Club of Rome in the early Seventies and had to experience a series of disasters of science-based technologies, culminating in the Tschernobyl catastrophe in 1986 in order to understand the fact that it would by no means be enough for mastering the fundamental problems in the relationship between modern science and recent society, if we could restrict all applications of science exclusively to peaceful purposes. To differentiate between use and abuse of science – as far as it is possible in a time when more and more products and technologies are fit for „dual use" – is an important matter, but it is no more than the top of the iceberg, since also beneficial use of science is unavoidably burdened with ambivalence.

Since then, the ongoing growth is perceived not only as a promise like in the past, but at the same times as a risk and threatening. The whole development often is estimated like the fulfilment of a natural law, a compulsion of facts („Sachzwang") that by no means could be changed and that had to be taken for given in order to find out some convenient way to adapt to the unavoidable. No moratorium for publicly criticized directions of research seems to succeed. „There is no alternative" – a slogan that is, nearly a century after the breakdown of classical determinism in physical world-view, among politicians one of the most favourite when they proclaim their ideas about future. The race for priorities, the rigor of competition, the head-hunting for profit-promising talents (a revealing example is the so-called Greencard action for information specialists in Germany) go on as intensively as never before. We are standing before the appearance of a law-like necessity, and the prerequisites to master the situation are rather poor, in any case not so good as they had been in the Seventies and Eighties when the science of science project flourished.

Nevertheless, the past period of systems confrontation implies an important historical lesson. Quantum physics, for instance, as treated by Fok in Leningrad or Rahman in New Delhi, was not very distinct from quantum physics we could read in Heisenberg's books or in the famous Feynman lectures – but the social context of scientific work in various parts of the world was significantly different, and so were the social implications of science. In other words: one and the same science evidently implied alternative and even contrary possibilities, and the competing societies could be seen – from an epistemological point of view – as a kind of experimental arrangement produced by history in order to reveal alternatives included in science itself. The lesson is that we might expect the existence of alternative developmental possibilities in science also in a homogeneous type of societies (like western capitalist democracies), although they are more hidden behind the curtain of apparently unchangeable trends.

Essentially the same lesson we can draw from history of science. Among scientists, the opinion is widely shared, that the kind of development, the feature of growth, the general method of thinking (scientific rationality) have always been the same, and was has remarkably changed is only the precision of knowledge, the amount of reliable results, the extension of scientific activity, and the velocity of growth. When D. J. de Solla Price started in studying the growth processes of science with the help of quantitative methods, especially statistics (the beginnings of the later on so-called scientometrics), he found for various kinds of indicators he used (number of publications, of scientists, of universities and so on) surprisingly stable growth patterns that were not seriously affected even by wars and crises and could easily be covered with simple mathematical functions (models of exponential growth and saturation). Psychologically, people experienced the transition from „little science“ to „big science“ in the late 19th and the early 20th centuries as a kind of explosion, as a sudden change from one quality of science to another, but Price explained that impression as an effect of immediacy, resting upon the same stable law of growth.

Regular time series of scientific growth indicators Price could trace back to the 17th century. In this century seems to have happened a kind of singularity in the development of modern science. Here the result of quantitative investigations met the traditional idea that this century had been the true birth time of science; thinking about nature in former times was qualified as a pre-scientific, philosophical, and speculative art, at best as pure collecting of facts („natural history“). Since about 200 years the overwhelming majority of scientists shared this view of history, meanwhile in the humanities the history of ideas was rather seen as a continuous process of perfection from antiquity up to our times. According to the common sense of naturalists (and many historians of science, too) there happened at the beginning of modern times the great scientific revolution bringing science into existence. There were at least two eminent heroes of the revolution: Galileo, who invented the method, and Newton, who constructed the first consistent theory, suited for experimental tests and able to explain and to forecast natural phenomena; the two heroes were surrounded by a circle of further outstanding personalities, like Descartes, Leibniz, Kepler, Huygens, and others, so that the establishment could be interpreted as a collective achievement. In a slightly modified version, each discipline could be ascribed its own revolution, namely at the moment when it was mature to adopt the mechanical model. Thus, chemistry had its glorious revolution, firmly connected with the name of Lavoisier, in the late 18th century, brought about by application of physical methods (measuring of mass, volume, or heat) and concepts (law of mass conversation) to chemical phenomena. The crucial point was that for each branch of science happened only one revolution, once and for all, which irrevocably separated pre-scientific and scientific stages of knowledge. All the former natural studies under the guidance of Aristotelian ideas were classified as pre-scientific.

Let us have a short look at the epistemological core of the Galilean turning-point. Designing a new kinematics, Galileo not simply improved the old medieval mechanics, but created an original approach in opposition to his precursors. The clue for understanding the principal innovation, introduced by Galileo into the method of knowledge production, is given in his famous dictum that the Book of Nature is written in mathematical language. The Book of Nature - a traditional metaphor in Christian culture, comparing nature as divine creation (natural revelation) with the Holy Scriptures – lies open before everybody's eyes, but people who do not know mathematics cannot correctly read it. Also the knowledge of mathematics only is not enough to explore nature in a Galilean sense, it is a necessary, not sufficient condition. Objects of nature are related to mathematical structures by measurements translating properties of nature into figures, and the situations appropriate for measuring must be at least carefully chosen, in common they must be artificially prepared by means of technical arrangements and experimental reshaping of native nature. It was really a revolution in thought, introducing the procedures of the crafts, hitherto applied only for practical needs, into the exploration of nature. The power of experimental method is rooted in the controlled change of nature by man for cognitive purposes, guided by theories that are expressed in a mathematical language, and it is linked with the predominance of analytical approach we had mentioned at the outset, the dissection and compartmentalization of nature. Many connections had to be neglected in order to get precise descriptions of reproducible facts.

Of course, the experimental method of modern science was by no means a personal invention of Galileo alone. The emergence of experimental method succeeded only in a tentative process with many participants on the one hand, and on the other, Galileo's approach was influenced by some inconsistencies and concessions to traditional modes of thinking. Nevertheless, the historical Galileo is more suited to serve as a symbol for the birth of modern science than any other among his learned contemporaries.

The contradiction between innovation and tradition can be clearly exposed. The old, Aristotelian natural philosophy was an immediate theoretical explication of common sense, of everyday experience. Everybody knew pushing a cart or pulling a carriage that he had to afford force permanently in order to maintain a straight-lined uniform movement. Therefore the corresponding statement of Aristotelian physics was immediately reasonable. On the other hand, nobody had ever experienced a movement, going on unlimited without permanent application of force. From an everyday point of view, it was impossible to agree with the Galilean principle of inertia, one of the basic principles of the new mechanics. J. Mittelstraß makes a principal difference between phenomenal and instrumental experience. Phenomenal experience, as it is codified in Aristotelian physics, comes directly from everyday practice. Knowledge of that type can never contradict experience; an epistemic system based on phenomenal experience does not contain an internal source and incentive of progress. Galilean science, in contrast, produces in artificial arrangements under theoretically and practically controlled conditions instrumental experience that is not compatible with everyday common sense. A connection between them does exist in one direction only. Scientific research can, in principle, explain phenomenal experience by analysing the ways of its constitution, meanwhile common sense is unfit for understanding science. Epistemic systems based on instrumental experience are designed to establish and to solve contradictions between theory and empirical data; therefore they include an internal source of advance.

Just this property lays the foundations for scientific progress as a self-determinating and self-reproducing process generating its own path-dependencies and producing in a methodologically (and technologically) controlled manner testable units of knowledge that can be accumulated (including the regular replacement of obsolete data by more precise ones) and combined into knowledge systems. What Price had registered, were the impressive external effects of this remarkable internal property of science. There are deep and meaningful analogies and correspondences between systematic production of scientific data and systematic employment of rational technologies in industry, and it seems to be much more than a superficial similarity that the historical way of science from the small experimental cabinets and modest personal laboratories of the 18th century to „big science“ corresponded to the development of economy from the workshops of craftsmen through manufactures and factories up to globally operating enterprises. Therefore it should be allowed to put the question whether the science of a post-industrial society should perhaps take on an essentially other form than the mere extrapolation of „big science“ that was the genuine scientific counterpart of large industry.

At any case – science of Galilean type has an enormous vitality and penetrating power that is not exhausted up to our days. It s not so decisive that mechanics was the first case, where the new style of exploring nature was implemented; the advantage was rather pragmatic, since the epistemic constellation there was fairly simple and lucid. Once established in the form of classical mechanics, the style of modern science gradually conquered the other branches of physics, chemistry, technology, important parts of biology, the geosciences, psychology, economy, and even sociology (social sciences). Expanding together with international trade and colonialism all over the planet, modern („western“) science nearly without any trouble pushed away traditional forms of knowledge closely connected with local cultures. For instance, after the Meiji reformation in 1868 Japan – a country with rich traditions also in the field of knowledge – suddenly „embarked on its wholesale importation of Western science and related institutions“. Only a few decades later several branches of traditional knowledge like Japanese mathematics (wasan) had changed themselves from vital components of local culture into a subject for historians.

In the early years of the 20$^{\text{th}}$ century, the clear picture of scientific advance began to be challenged. Meanwhile other fields continued to reshape their domains according to the model of classical physics, fundamental changes began in the very centre of physical theory that could no longer be interpreted as further advance within a given framework, but had to be seen as a reconstruction of the framework itself. Physicists gradually got accustomed to make a difference between classical physics from Galileo and Newton up to Maxwell and Helmholtz, and modern physics associated with Quantum Theory, Special and General Relativity and the names of Planck, Einstein, Bohr and many others. Hesitatingly the concept of scientific revolution came into use applied to the transition from classical to modern physics. The terminology implied a crucial problem in understanding scientific progress. If physics had passed at least two revolutions and the first of them had led from the pre-scientific to the scientific stage of the field – does it mean that the second revolution had been of a minor order of magnitude as compared with the scientific revolution of the 17$^{\text{th}}$ century, because it was a revolution within science, and, consequently, must have left untouched some fundamentals of classical physics? This is a difficult historical question implicitly penetrating the vast amount of literature about the relationship of classical and modern physics.

The problem had the quality of a Gordian knot, and only in the Fifties a young American physicist who had converted to history of science developed a fresh and original approach to cut it. His name was Th. S. Kuhn, and he became world-wide known when he published in 1962 his remarkable book *The Structure of Scientific Revolutions*, an imaginative study that received a lot of editions and translations in many countries. His central idea was that mature fields in science tend to adopt fairly closed paradigms able to organize the whole field of knowledge and to guide the complex of research directed to the extension of the given field. Scientists, according Kuhn, do not use an accepted paradigm like an external instrument one can change at will; rather they are living inside the paradigm and looking at the world through the paradigmatic structure. Therefore rational arguments and experimental evidence may shake a paradigm, but they are not enough to persuade a scientist for leaving it; there must happen a kind of „gestalt shift“ transferring the scientist from one intellectual (and sensual) world into another. Every branch of science may pass a sequence of paradigms and thus a sequence of different revolutions, and it may sometimes be characterized by competing concepts. It is evident that Kuhn's theory of scientific revolutions weakened the rigid distinction between pre-scientific and scientific knowledge and changed the concept of scientific progress. In a Kuhnian perspective, for instance, the chemical revolution of the 18^{th} century has to be interpreted not as the original establishment of chemistry as a science by Lavoisier, but rather as a shift from one chemical paradigm to another. Inspired by Kuhn's ideas, E. Ströker had created an outstanding, subtle, and deeply differentiated picture of the transition from phlogistic to anti-phlogistic Chemistry.

During the last decades, Kuhn's concept has been ground in the mills of scientific criticism. But apart from the problem of the validity of his theory in detail (that cannot be discussed here), his courageous attempt had essentially stirred up the rather simple and linear traditional view of scientific progress and has enhanced the attentiveness for conceptual plurality and heretic phenomena in the history of science. The traditional picture of advance in science was rigid and connected with the claim of monopolies (criteria of „Wissenschaftlichkeit“). A Kuhnian view, on the other hand, would be rather soft and would pay attention on alternative trends in science existing in the shadow of ruling paradigms and often discredited as merely philosophical, „speculative“, pseudo-scientific and so on. So it has to be noticed that the mainstream of dominantly analytical approaches had always been accompanied by more synthetic tendencies of thought stressing the complexity and wholeness of nature – trends that were usually marginalized and held a place only at the periphery of dominant scientific culture. Sometimes they reached a little more visibility, for instance in the era of romanticism or in encyclopaedic panoramas like the Humboldtian „Kosmos“. Generally, however, they could only develop under the auspices of philosophy in the outer court of science; mainly dialectical philosophy acted for a long time as a defender of a complex, integrated, and evolutionary world-view against the analytical mainstream of science.

Among scientists, the prevailing attitude towards dialectic was a kind of condescending ignorance appreciating it as a phenomenon that stood outside of science and was not important for doing science. Nevertheless, dialectic thought had the capacity to act as a useful companion of science, persistently reminding the specialists that the relations they had methodically neglected really existed in nature, and to keep alive the ideas of complexity and evolution until science itself would be mature enough to approximate these subjects with its genuine instruments (for instance, the recent theories of self-organization). Dialectic may be, more reasonable, regarded as a cultural resource of science, influencing the constitution of paradigms, the interpretation of theories, the design of research strategies, and the choice between different options in favour of diversity, complexity, historicity, unity of man and nature, and human values. Perhaps the most important link bridging the gap between analytical science and the requirements of a synthetic world-view was the combination of analytical process-units to features of cyclic structures and interactions that were able to explain self-reproduction (thus also dynamic stability) and even self-evolution of natural systems. There are, for instance, in the early years of modern science Copernicus' heliocentric system with the idea of planets revolving around the sun or the detection of blood circulation by Harvey, later on the concept of economic equilibrium maintained by cycles of exchange (Quesnay), reproduction (Marx), and innovation (Schumpeter), the concept of thermodynamic cycles allowing to demarcate between reversible and irreversible processes, the identification of numerous cycles of biochemical reactions in metabolism up to Eigen's hypothesis of hypercycles used to explain the origin of life, the idea of automatic control systems and feedback in cybernetics and many other examples. Thus it can be argues that science has reliably paved the way previously in smooth contours suggested in dialectical philosophy.

Perhaps the greatest triumph of complex thinking in cyclic dependencies is the rise of ecology from a biological specialty to a general concept penetrating various scientific disciplines as well as responsible economic and political strategies and affording effective instruments for a critical evaluation of recent tendencies to pull down the walls of social control for boundless and irresponsible globalisation. The Russian mineralogist and geochemist V. I. Vernadskij, as a result of his profound studies on the migration of chemical elements in the earth's crust, had formed the idea of living nature and human society as geological agents, introduced the concept of biosphere and adopted the concept of noosphere from the heretic theologian and naturalist Teilhard de Chardin. The cluster of ideas presented by Vernadskij and developed already in the Twenties, was a candidate for a new paradigm, integrating numerous disciplines from an ecological point of view and modelling earth together with living nature including human society on its surface as a subtly balanced hypercomplex system with a multitude of integrated cycles on various levels of organization. Given the fact that the impact of society on nature has reached geological dimensions, the Vernadskij paradigm included the ethical requirement that mankind is responsible for the maintenance of global balance. Vernadskij's ideas might have been an appropriate foundation for investigations in global ecology, but they were not perceived in western countries. Therefore the Club of Rome, dealing with situation and perspectives of our global system, had to develop its own philosophy, revealing many similarities with the noosphere concept.

Almost thirty years after the first report to the Club of Rome, there are many good reasons for the position that we have to choose between boundless growth and a sustainable development on the stable ground of global equilibrium and that only the second option would be a good choice. A. King and B. Schneider had characterized the transition to sustainability as a „global revolution“ changing all aspects of human life including science. As they are arguing the challenges of the global revolution would require a re-orientation of R & D programmes and a radical change of research priorities. The urgent meta-task for the whole system of modern science should be the exploration of resources and procedures for co-operative global regulation that has – in the opinion of the Group of Lisbon – to replace the unrestricted competition in global economy. Profoundly criticizing the „myth“ of growth, the Club of Rome „classics“ argue that a society in global equilibrium, at least partially relieved from material privation and pursuit of profit, would dispose of hitherto unexpected possibilities for constructive creativity.

The cognitive nucleus of modern western science, deeply rooted in our social and economic system as well as in our cultural traditions, from Galileo's times up to now remained the subject-object-relation between man and nature, including distance and objectivity, but also domination and exploitation – a relationship favourable for the scientific enterprise, but not secured against the risk of loosing the internal measure given by the simple fact that man will always be a part of the world and cannot take the position of an unlimited outside ruler. Global ecology may be considered as the hitherto most powerful impetus for re-formulating the epistemological approach in science. It is not improbable that global ecology will be restricted to the role of one scientific discipline besides others. But when global ecology becomes the leading paradigm of modern science, it may succeed – integrating mental resources from non-european cultures – in solving a fundamental problem that all the paradigm shifts during the last 400 years had left unsolved: the reconciliation of Man and Nature.

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