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Global history of science as a knowledge resource for the Anthropocene

Matthias Schemmel

Max Planck Institute for the History of Science, Berlin, Germany

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Author for correspondence:
Matthias Schemme,
E-mail: schemmel@mpiwg-berlin.mpg.de

Non-technical summary

The article addresses the role of science in the present global ecological crisis, both as a factor in bringing it about and as a means to confront it. It is argued that the history of science, pursued in a global and long-term perspective, is an important knowledge resource for understanding the development of science in society. Pivotal episodes from that history, ranging from the origin of science in antiquity via the early modern scientific revolution to recent developments in industrial societies, are discussed with a particular emphasis on the case of China and with a view to the present crisis.

Technical summary

In this contribution, examples from the global, long-term history of science are used to illustrate characteristics of the historical development of science that are considered important in the context of the question of the role of science in the Anthropocene. In particular, it is argued that certain central features of modern science, such as its production of surplus knowledge (i.e., knowledge not immediately useful for the material reproduction of society) and the crucial role of technology in the scientific experience of nature, are actually very ancient in origin and, contrary to widespread views, not at all essentially 'Western'. The comparison of different origins of science in antiquity reveals cross-cultural similarities as well as culture-dependent variations that suggest the existence of alternatives in the development of science from early on. Further emphasis is put on the fundamental role of the societal embedding of science and the force of path dependence in the historical development of science. The paper concludes with a few preliminary thoughts and questions on what these findings tell us about the necessary transformations of science in the Anthropocene and how they can be brought about.

Social media summary

The global history of science is argued to provide an important knowledge resource for the Anthropocene.

1. The challenge of the Anthropocene

There is an ongoing debate among geologists as to whether the Anthropocene constitutes a geological epoch in its own right.[i] But regardless of what decision on this matter will eventually be taken, there can be no doubt that humanity as a species is changing the ecology of the entire planet in ways that endanger the well-being of present and, more so, future generations, including the possibility of rendering large parts of the planet (or even the entire planet) uninhabitable. Science plays a fundamental role in these destructive developments. It is our use of modern science and technology that has amplified our powers to interfere in natural processes to such a dangerous extent. Science-based industrial production, including agriculture, lies at the core of the most destructive processes, such as the acidification of the oceans and global warming. This way of production also enabled the world population to grow to its present extent, thereby magnifying all problems through sheer quantity. But also more directly, science produces new and as yet incalculable risks (e.g., through nuclear technology or genetic engineering).

In view of the damage and the dangers that may directly or indirectly be ascribed to science, one may dream of 'simpler times' when science played no effective role in the material reproduction and maintenance of human societies. But doing away with science is not an option for humanity. Science and technology are the tools by which we detect and assess ecological changes, by which we contain imminent threats and by which we may find new and more sustainable ways of living. Science is not only a crucial part in the fabric of modern societies, it has become indispensable in confronting present and future challenges of society and in solving the very problems it partly helped to create. Beyond this, as I shall argue at the end of this contribution, science has become essential in shaping our view of the world and how we conceive of our place within it. It thereby contributes to the knowledge we need to re-orientate ourselves as individuals and societies and, ultimately, as a species in the Anthropocene.

The Janus-faced character of science is not new per se, but the actual global ecological crisis adds new urgency to endeavours to understand it better and to act in accord with such an improved understanding. How do we have to change the ways we do and use science in order to reach a more balanced and sustainable interaction between humans and their environment? How can such transformations in science and society be brought about and how can they continuously be shaped and directed? Clearly, to approach questions of this kind we need an understanding of how science functions in society and an idea of what science is and how it develops in its societal embedding.

In this contribution, I will use examples from the global, long-term history of science to illustrate a few characteristics of the historical development of science that I think are important in this context. In particular, I will argue that certain central features of modern science (such as its production of surplus knowledge (i.e., knowledge not immediately useful for the material reproduction of society) and the crucial role of technology in the scientific experience of nature) are actually very ancient in origin and, contrary to widespread views, not at all essentially 'Western'. I will do so by discussing the multiplicity of the origins of science in antiquity, which reveals cross-cultural similarities as well as culture-dependent variations. These variations show that there are alternatives in the history of science – that there is no predetermined one-dimensional logic of development. After that, I will further explore the factors conditioning knowledge development. I will argue for a fundamental role of the societal embedding of science, but also emphasize the force of path dependence in the history of science: the space of possible developments at each point in time is conditioned by the knowledge resources available in a given society at that time. Therefore, once science has become global, this raises the stakes for alternative solutions and the integration of local knowledge resources. I will conclude with a few preliminary thoughts and questions on what these findings tell us about the necessary transformations ahead of us. What kind of knowledge is needed and how can it be developed and acted upon?

I will time and again choose examples from the Chinese history of science. This is not only meant to serve the regional perspective that this publication is dedicated to, it is also intended to show that the pertinent questions concerning the relation of science and society are not primarily and not essentially 'Western' questions. The Anthropocene, if we take that concept seriously, is per se a global phenomenon, and to deal with it properly we have to recognize its global roots. It is true, historically as well as at the present, that power – and thus, by implication, blame – is distributed unequally among different regions of the world, and also within single societies. Industrialisation originated in Western Europe, and its global spread is inseparably linked to colonialization and coercion. But this does not mean that science and its role in modern societies can be readily described as essentially 'Western'. The rise of science in early modern Europe and its later function in industrialized societies are part of a global history of knowledge whose understanding is not helped by facile dichotomies between 'East' and 'West'. Such understanding rather requires careful study, in a cross-cultural perspective, of the relations between social and economic developments on the one hand and the history of knowledge on the other.

2. The multiple origins of science

Exactly when science begins in human history very much depends on how we define it. But no matter how narrow or wide a concept of science we want to apply, a crucial step towards what we now call science was made when knowledge was considered for its own sake, with no immediate practical goal in mind.[ii]

The earliest documented instance of this type of supra-utilitarian, or explorative, form of knowledge dates back to the Mesopotamian scribes of the early second millennium BCE, who explored the knowledge structures inherent in their symbolic means for land and labour management. These symbolic means, proto-numbers and a kind of proto-geometry, had developed in the practical contexts of administration, an administration that had become necessary in connection with the development of ever larger settlements, the early city-states. Internal difficulties in the administrative processes such as converting between the various systems of weights and measures eventually brought about the development of the sexagesimal place value number system of Old Babylonian mathematics. The system and its application implied a more general concept of number than the context-specific counting systems that it emerged from and that were further used in parallel to it.[iii]

But "these developments in the concept of number are not in themselves sufficient to explain the veritable explosion of evidence for supra-utilitarian mathematics in the early second millennium BCE," as Eleanor Robson explains in her highly recommended book on *Mathematics in Ancient Iraq* (Robson, 2008, p. 84). It is now broadly agreed that such a supra-practical form of mathematics first developed in the context of schooling.[iv] The administrative practices had to be learned, and the context of schooling is a first step away from immediate practical use. It allows for the exploration of the cognitive structures inherent in the material means of mental labour such as number symbols or line diagrams. In order to "account [adequately] for the turn to literate mathematics in the early second millennium [BCE]," Robson explains, "… it is necessary to factor in the ideology of the state under which the trainee scribes were preparing to serve" (Robson, 2008, p. 123). And she goes on to explain:

> [The] formalised discourse of measurement and rectification was, at one level, simply royal ideology in another form, promoted through practice and through literary representation. Just as Sumerian literature taught not only Sumerian literacy but also what it meant to be professionally literate, Old Babylonian mathematics carried similar messages about the abstract principles of numerate justice as embodied in the correct calculation of lines and areas. … [F]or their producers and consumers [Old Babylonian literature and mathematics] represented above all idealised abstractions of the ordered urban state, with god, king, and scribe at its centre. (Robson, 2008, p. 124)

Summing up, it was most probably in the context of schooling and owing to their position within the state hierarchy that the activities of the scribes and land surveyors departed from the direct application to practical problems of society and evolved into an exploration of the structural implications of the material and symbolic means of mental labour, a process that led, among other things, to the development of an abstract concept of number.

Similar developments must have taken place more or less independently in other early civilizations in Egypt, India, China and Meso-America, but they are not nearly as well documented as in the Mesopotamian case with its durable clay tablets. In

China, ancient mathematical works such as the *Suanshu shu* 筭數書 (ca. 200 BCE) and the *Jiuzhang suanshu* 九章算術 (probably first century CE) document later stages of the development of number.[v]

Our example illustrates how science emerges from systematic reflection on non-scientific, practical forms of knowledge. In this process, the social, material and intellectual means of reproduction of a given society not only bring about knowledge, which is then theoretically reflected upon in science: they first bring about the social structures and institutions through which this happens, the material means of mental labour necessary for this to happen and even the very cognitive structures from which such development of theoretical knowledge starts.

But owing to its explorative character (i.e., the pursuit of knowledge for its own sake), science cannot be reduced to the practical knowledge underlying it. Science produces a surplus of knowledge, which is not practical to begin with. The surplus knowledge has to be 'applied' in order to become practical again. Over the course of history, the production of surplus knowledge and its applications bring about a deeply structured body of scientific knowledge. Only think of the central role in science of arithmetic and geometry, whose practical origins we have just mentioned, and of later branches of mathematics, which build on them. Another prominent example for surplus knowledge from later times is that of electrodynamics acquired in institutions devoted to basic research such as the Royal Institution of Great Britain. Based on technological developments made possible by the growing chemical industry, in particular the electric battery, electromagnetic phenomena were systematically explored and theoretically described long before radio transmission and other path-breaking applications were envisaged.

Today, science is highly structured by disciplines and subdisciplines, which display different degrees of closeness to application. There are, for instance, elaborations of theory that are, at the same time, deliberately pursued in the direction of certain fields of application. This complex array of a disciplinary division of labour in present-day science and the long-term development of surplus knowledge have to be taken into account when thinking about future transformations of science and how to direct them. Science may neither be shaped at will, ignoring its internal rationality and the resistance of its materiality, as the failures of Lysenkoism have unmistakably shown,[vi] nor does science represent a closed system whose development is entirely determined by an internal dynamics, as is already evidenced by the competition for, and the political and economic motives behind, funding.

Another important aspect of science is that its experience of nature is almost always mediated by technology. This is obvious for the above example of electrodynamics and applies to all 'natural' sciences, even including biology. But it even holds long before the rise of systematic experimentation. It is documented, for instance, in the so-called *Mohist Canon* 墨經, a Chinese source stemming from around 300 BCE, a time referred to as the Warring States period. The text originated under socio-political circumstances radically different from those of Old Babylonian mathematics. Rather than having served the positioning of a class of scribes within a centralist royal hierarchy, the Mohist tradition flourished in the context of a competition between different groups who offered their advice to the kings and rulers of the various small states into which China was then fractured.

The Later Mohists attempted to show that their vision of an ethics anchored in the realm of human beings, without recourse to deities, was indeed viable.[vii] To this end, they had to show that all sorts of conundrums and paradoxes could in fact be resolved through rational argument and the careful use of language. In this attempt, they reflected not only on semantics, but also on phenomena brought about by mechanical and optical devices. For instance, they explain the diverging effects of equal weights on lever arms of different lengths by introducing the concept of the 'effectiveness' (*quán* 權) of a weight, and they explain the inversion of images in pinhole constructions and concave mirrors by assuming light to proceed along straight lines and by introducing certain crossing points.

Mohist science has sometimes enthusiastically been likened to ancient Greek science. Thus, Joseph Needham, in his pioneering work on the history of science in China, suggests that the Mohist passage on the lever is equivalent to Archimedes' full-fledged theory of equilibria.[viii] But such projection from the Western history of science onto the Chinese tradition is problematic, not only because it has to postulate things that are not found in the historical record. More fatally, it assumes that there is only one possible course of history, the Western one, and the non-Western examples are then judged by how close they come to it. I would rather suggest that we see Mohist science as an independent and genuinely alternative origin of theoretical science. Only then are we able to appreciate the commonalities and differences between the two traditions and thereby distinguish between the cross-cultural characteristics of theoretical knowledge and historical contingencies.

Both traditions of knowledge, that of Greek science and that of Mohist science, result from a reflection on existing knowledge.[ix] This existing knowledge is frequently practical knowledge and is connected with the instruments and the technology of the time, such as mechanical devices involving a lever or specifically shaped mirrors. The knowledge that emerges from reflection on the linguistic representation of practical knowledge is no longer practical but theoretical. Its objective is not to solve practical problems but to organize knowledge itself. The practical knowledge reflected on often turns out to be the same in both cultures. To some extent, this could be due to material conditions that are independent of culture and therefore universal. It could also be a result of a previous transfer of knowledge when, for instance, tools and technology – and with them the corresponding knowledge – were exchanged. Nevertheless, reflective thinking occurred independently in each of these societies; there was no exchange of theoretical texts. Consequently, these two processes of reflection also produced different results. The theoretical terms of the two traditions differ and partly reflect the different discursive contexts in which these reflections took place. While the Mohists react to the so-called dialecticians, or *biànzhě* 辯者, of Warring States China, the earliest text on mechanics in the Greek tradition, the *Mechanical Problems*, attempts to integrate the new knowledge into Aristotelian natural philosophy. This reflects a different timing of the development of specific types of intellectual activity in the two societies: while in the Greek case the reflection on language occurs only *after* the creation of encompassing cosmologies, in the Chinese case the Later Mohist reflections *predate* the rise of the syncretistic Yin-Yang 陰陽 cosmology.[x]

The existence of the Later Mohist tradition within Chinese intellectual history corroborates another point of importance in the context of our discussion: there is no facile dichotomy between Eastern and Western ways of thinking about nature. There is the widespread idea in Western literature on China that the Chinese conceived of the human individual, society and nature as an unseparated oneness, while only the

Europeans had a concept of nature.[xi] This often comes along with the idea that East and West were operating on wholly different modes of thinking about the world, that Chinese thinking was of the correlative type as exemplified by the Yin-Yang and Five-Agents 五行 scheme, while European thinking was analytical and causal. Such generalizations do not hold up to historical scrutiny. If one chooses to distinguish between correlative and causal types of thinking about nature, one will find historical instances of both in both cultural realms; the *Mohist Canon* clearly falls in the latter category. There is no basis for claiming the one type of thinking to be "a primordial and quintessential expression of the 'Chinese mind'"[xii] – and the other of the 'Western mind', for that matter. We see different knowledge traditions develop under different social, political and economic conditions. They may become dominant or characteristic for a culture owing to the path dependence of the history of knowledge. But even in this long-term perspective they remain dependent on the material and societal conditions under which they thrive. This shall now be looked at more closely.

3. Path dependence in the history of science

Although ancient science was, to a large extent, a reflection on the material means of production, it did not contribute to material production in any significant way. This may explain its marginal and often precarious status throughout antiquity. The Mohists probably ceased to be a vital tradition of thought by the time the Qin 秦 unified China in the third century BCE. Ancient Greek science, although much more widespread as a cultural practice in Hellenistic times than Mohist science ever seems to have been, did not survive late antiquity in Europe and had disappeared in the early Latin Middle Ages. Much of the Greek heritage was only preserved through its transmission in the Arabic World.

The situation of science with respect to material production was not radically different at the beginning of the early modern era in Europe. Despite the fact that early modern engineer–scientists like Galileo Galilei claimed that their 'new sciences' were useful in practice, the surplus knowledge of science became relevant for material production only very gradually. In order to explain the acceleration of the production of scientific knowledge in early modern Europe and its continued institutional maintenance, we have to invoke its political–ideological function in the social struggles of the time.[xiii] Science, in revolutionizing natural philosophy, was instrumental in constructing encompassing counter-worldviews to the traditional feudal one. It thus came with a promise of enlightenment. At the same time, through its origins in practical mathematics, it featured closeness to technology and material production, which implied the promise to improve them. In other words, it promised empowerment.

The role that the socio-political function of early modern science played in its emergence and early development becomes even more evident when we compare the European case with the alternative development in China.[xiv] Joseph Needham raised the question of why Chinese society, despite its long and vivid traditions of technical engineering and natural philosophy, did not bring about modern science.[xv] This question becomes even more pressing once it is considered that through the presence and activity of the Jesuits, the Chinese elites had access to a large portion of European scientific knowledge exactly at the time when the rapid transformation of the European knowledge system took place. While Europe was experiencing the expansion of knowledge that later came to be known as the 'Scientific Revolution', technical and scientific knowledge was transferred to China on a large scale.[xvi] Prompted by the interest of the Chinese elites in European knowledge, Jesuit missionaries mounted a large-scale campaign to systematically bring European knowledge to China. Thousands of books were shipped to China, astronomical instruments were built, cannons were cast and Jesuit experts were appointed to work on the calendar and survey the land. Jesuit and Chinese scholars cooperated on countless translation projects to make the foundations of European science and its latest findings accessible to readers in China: from Euclid's *Elements* in Christoph Clavius' edition, which had just been published, to Galileo's telescopic discoveries.[xvii] And even fields that had fallen into oblivion since the Mohists and were no longer prevalent in the Chinese knowledge tradition, such as theoretical mechanics, became part of this campaign. The *Yuanxi qiqi tushuo*, the book of *Illustrations and Explanations of the Wonderful Machines of the Far West*, which appeared in 1627, presents Chinese readers with the latest theorems of a Simon Stevin or a Guidobaldo dal Monte (Schemmel, 2013; Zhang *et al.*, 2008).

If we were to assume that it is knowledge alone that produces a scientific revolution, we should expect to have seen a similar development in China during the seventeenth and eighteenth centuries. But instead, the Chinese knowledge system remained largely stable. Ultimately, it was the Chinese knowledge institutions – such as the Bureau of Astronomy at the imperial court and the imperial examination system – that shaped the fate of the new knowledge. The elements of Western knowledge that could be assimilated to the Chinese system were incorporated, while other elements, such as theoretical mechanics, remained on the margins. Unlike in Europe, new practical knowledge did not come into conflict with traditional worldviews in China. The question concerning the true world system, whether helio- or geo-centric, which was so contentious in Europe from both a religious and political perspective, failed to spark an equivalent conflict in China. The Chinese system of knowledge in the seventeenth century and its societal embedding were so stable that they even survived the decline of the Ming 明 dynasty and its fall in 1644 followed by its replacement with the Qing 清 dynasty, a Manchurian foreign rule. The embedding of scientific knowledge in a broad system of knowledge and this system's embedding in society seem to have had at least equally significant impacts on the development of knowledge as the knowledge itself.

This shows the extent to which the development of science is contingent on societal conditions. But this does not mean that scientific methods, ethos, concepts and results may be shaped at will. Although allowing for alternatives, the development of science is path dependent (i.e., its future development is contingent on its development up to the present). In this context, it is not only social and political conditions that play a role, but in particular material conditions such as technology and the shared knowledge of the time, including the symbolic means of knowledge representation. Works such as Mario Biagioli's *Galileo Courtier* (Biagioli, 1993) may explain how the politics of patronage shaped Galileo's career, but what do they tell us about the overall development of early modern science? Let me illustrate the conditioning force of shared knowledge using an example.

A couple of years ago, I had a friendly dispute with Stephen Pumfrey about the position in the history of early modern science of Thomas Harriot, an English mathematician and philosopher contemporary with Galileo. I claimed that Harriot was an 'English Galileo', while Stephen denied that Harriot was one (Pumfrey, 2003; Schemmel, 2003). And I think we both had a point. He approached the question from the perspective of patronage studies and concluded, among other things, that the English situation prevented Harriot from publishing. As a result, Harriot could not promote his scientific findings in the way his famous Italian contemporary did. In particular, he did not nearly as often explicitly relate his findings to the ideologically charged discussions of world systems and worldviews of the time.

I approached the question on the background of my reconstruction of Harriot's work in mechanics from his extant working notes.[xviii] I found out that Harriot, using mathematics and experiments, had independently arrived at more or less the same results as Galileo. He discovered the law of fall and the parabolic shape of a projectile's trajectory, and he assumed that all bodies fall with the same speed in a vacuum, just to give a few examples. Thus, the cornerstones that were important for the later development of classical mechanics were all there. What is more, Harriot even encountered the same difficulties as Galileo. He and Galileo were, for instance, both unable to derive from sound physical principles the upright parabola as the trajectory resulting from oblique projections.

This underlines my argument above. The material means of reproduction, including contemporary technology such as canons, and the material means of mental labour not only provide the theoreticians at a certain time with a certain set of challenging objects of study. They also provide a shared set of conceptual and symbolic tools, methods and procedures for solving problems, practical experiences to be taken into account and even structures of thinking that developed in these practical contexts. This shared knowledge defines a space of its possible transformations and thereby conditions the individual theoreticians' work, independent from the concrete political situations they find themselves in. It thus defines what scientific rationality means in the given historical situation.

The relative autonomy of the internal dynamics of knowledge development following from this historical rationality has only expanded since early modern times. Through mathematical elaboration of physical theory, through experimental penetration of realms ever more remote from everyday experience, through the related and continued disciplinary differentiation and ensuing attempts at reintegration, the space of solutions to the problems of basic science appears (*pace* Forman's thesis) entirely decoupled from developments in other parts of society.[xix] From this perspective, it would seem that science cannot be politically directed, that attempts to do so can only be detrimental to science and that one must let it grow 'naturally'.

There is a counter-trend to the expanding relative autonomy of basic science, which is equally important. Paradoxically, the interrelation of the system of scientific knowledge with the material and technological development of society has increased, too:

> Over the course of the nineteenth century, science began to have a major, global impact on human life. New fertilizers, new means of transforming energy (e.g., the steam engine), new means of communication (e.g., the telegraph), new measures against widespread diseases (e.g., antibiotics and vaccination), and new materials would have been inconceivable without the close association between science, technology, and social and economic development. (Renn, 2020, p. 223)

The crucial and still expanding role that science has assumed for the material reproduction of society since the Industrial Revolution has repercussions on the development of science itself. Not only do developments in industry make new branches of science possible in the first place (the battery for electrodynamics and the black body for early quantum mechanics are examples), concrete demands from governments and corporations directly shape large parts of scientific research (the Manhattan Project, nuclear energy, genetically modified food).

We are thus not dealing here with a simple question of the application of scientific surplus knowledge to certain demands of society, but with the co-evolution of scientific knowledge and practices on the one hand and the industrialized societies of which they are an integral part on the other. We may thus speak of a self-reinforcing feedback loop between different forms of knowledge (Mokyr, 2002, *passim*) and "between knowledge and material economies" (Renn, 2020, p. 222). This feedback loop, the beginnings of which can be identified in early modern Europe, has to be taken into account when discussing different developments in different parts of the world, and especially the question as to why among the several regions of the world that had developed proto-industrial ways of production, it was Western Europe, and England in particular, that first made the transition to industrial production.[xx]

The violent global expansion of European outreach and control was not only a consequence of industrialization, but also a condition for its coming into being in the first place and for its maintenance, in many respects up to the present. This expansion also relied on the particular European feedback loop between knowledge development and material production, from the art of navigation to the production of steam-driven gunships. The Chinese example shows that the relation between the power of the industrialized nations and their science was recognized by historical protagonists. Already in the Self-Strengthening Movement in China beginning in the 1860s, scientific knowledge was counted among the things to be adopted (Hsü, 2000, p. 282). Later on, besides translations of Western works on science, increasing efforts were made to institutionalize systematic science education. Universities were founded following the Western model, and in 1905, the imperial examination system, which had existed for more than a millennium, was abolished in favour of strengthening science education.[xxi]

While at the time of the Jesuits the Chinese knowledge system had remained unshaken, China now entered an intricate process of adoption of modern science. Somewhat reminiscent of the case of early modern Europe, science was again perceived as a promise of enlightenment and empowerment, such as in the context of the May Fourth Movement of 1919. Over the course of the twentieth century, the Chinese knowledge system was completely restructured, eventually leading to the full and systematic implementation of science and scientific technology through institutions of education, research and development. Today, China is a leading contributor within a global culture of science and technology.

Modern industrialized China thus provides evidence for a strong convergence in the global development of science and technology. Once the alliance of science, technology and industrialized production came into being in one region of the world, it spread globally, displacing other forms of material reproduction of society; it seems to have done so regardless of religious and philosophical traditions and over a variety of political systems. To be sure, not all geographical regions are industrialized to the same degree. In fact, global differences in industrialization are constitutive features of how the present-day global economy works – just consider the role of regional differences in labour costs and the extraction of natural resources by non-local corporations. Nevertheless, techno-scientifically driven industrial production, including agriculture, has become a global phenomenon. Global competition, militarily and economically, is arguably a major factor forcing convergence in this process. Looking more closely at the development of science and technology in twentieth-century China, it is full of decisions, from the development of nuclear weapons to the promotion of private transport and the car industry, which are clearly modelled after other nation's experiences.

4. Towards a science for the Anthropocene

Turning back to our initial question of how to confront the challenges of the Anthropocene, we then see that the global exploitation of our living environment cannot be overcome simply by nurturing certain ideas about the relationship between humanity and nature. We cannot change the world-historical entanglement of science and modern society by simply recognizing "nature as another subject [i.e.,] as opposing partner instead of object,"[xxii] or by deflecting to allegedly characteristically Eastern ideas about the unity of humans and nature. As I have tried to argue above, the scientific experience of nature is from its very inception – and irrespective of historical period and culture of origin – fundamentally linked to technology. This characteristic trait of science was crucial for science eventually to become a major force of production in modern societies and, by now, a prerequisite for the reproduction and maintenance of human societies globally. While the path dependence of its development implies that its particular present form bears witness of its historical development (e.g., its momentous expansion in early modern Europe and its spread through its role in industrialized societies), science has thus become a potency of the species.

Its significance as a potency of the species raises the question of whose science it is in practice: to whom is it available, who decides about its direction and who has access to its results?[xxiii] Although science has become global, participation in it is still very unequally distributed. This is a problem of democracy within single societies, and also a problem of democracy on a global scale. For instance, does science serve local communities in their struggle for empowerment and in preserving local ecologies, or does it serve the special interests of large trans-national corporations with their inbuilt zeal for the maximization of profits? While 'citizen science' of the kind that emerged in the wake of the Chernobyl and Fukushima disasters is an example of new modes of knowledge production, created locally but speaking to global issues of the Anthropocene, the globalization of science and technology by itself has not resolved the fundamental problems of science serving society, as the very occurrence of these disasters cruelly demonstrates. On the contrary, the space for alternative approaches appears to have been reduced in the course of globalization. The globalization of science is part of the processes of economic and geopolitical globalization. As a consequence, it forces the political and economic decision-makers to follow apparently successful examples, as I have argued above for the case of modern China. Once the participation of a nation in global science and technology is achieved, the direction of influence can also be reversed, of course, as the debated role of Chinese companies in the establishment of the 5G network indicates. So while historically science has had alternative origins and many independent developmental threads, the globalization of modern science has merged them, either by extinction or by integration, into one global thread.

There is an inherent contradiction in the present relation between this global science and global society. Scientific rationality with its claim to universality is inherently democratic. The liberating potency of science has been a driving force for its promotion many times in history; I have mentioned the promise of enlightenment and empowerment that motivated its promotion both in early modern Europe and in early twentieth-century China. Surely, then, global science should serve all humankind. This is indeed what is often claimed it does. But the way the larger part of scientific activity worldwide is in the hands of special interests, economic or national-strategic, and the way in which science is at the disposal of large trans-national corporations, who furthermore have a disproportional influence on government decisions on its use and direction, contradict this democratic potential. This lack of democracy lies at the core of the involvement of science in highly destructive global developments such as the economic exploitation of whole countries and regions, the potential and actual devastations related to the continuing optimization of the technological means of warfare and the increasing destruction of the natural basis of human life on Earth for the short-term goals of particular groups. In their destructiveness, these developments are highly irrational, which should be clear per se, but becomes even more obvious on the planetary scale and from the viewpoint of humanity as a whole. At the same time, these irrational developments are promoted using the powers of scientific rationality. Science has become complicit in unreason.

This is not merely a problem of politics, the application of science or of science policy; it is also a problem of science itself. In order to take responsibility for its own development, science has to reflect the social and ecological consequences of its results. It has to extend its rationality to include its own interaction with society and nature. It has to take the limitedness of the planetary ecology into account. It has to take reproductive cycles into account and to think of humans as taking part in them, not just interfering with them, but keeping them sustainable. In certain fields, such as ecology, climate research and earth system science, this is already happening. But how can such a transformation be achieved for the whole of science? Using examples from the long-term history of science in China and the West, I have indicated ways in which the development of science is dependent on its societal embedding. To achieve such transformation, it then seems, science has to be in the hands of society (i.e., democratically controlled from the local to the global levels).

The necessity to intervene in the relation between science and society has long been understood at the former Max Planck Institute for the Study of the Living Conditions of the Scientific-Technical World. In the early 1970s, they already demanded the development of

> a theory of the social constitution of science which explains in what sense science and society are interrelated so that a selective determination of the former by the latter is in fact possible. (Böhme *et al.*, 1972, p. 302)[xxiv]

At the time, they relied on the theories of Thomas Kuhn, Imre Lakatos, Alfred Sohn-Rethel and others. To approach these problems on the basis of our present understanding of the specific historical nature of scientific rationality that I have tried to sketch in this contribution is, in my view, a worthwhile project. It would mean using the global history of knowledge as a means to understand the profound way in which the relation of science and society is built into scientific truth, but also how the material dimension of science provides it with an internal dynamic that brings about the generation of surplus knowledge. This understanding could then serve as a basis for exploring possible future transformations of science into a science for global sustainability. Such a research programme goes far beyond the scope of the present contribution, of course. Here, I only wish to bring attention to the desirability of such research, which would stand in the tradition of reflections on science and society.

Now, reflection on human actions is traditionally a task for the humanities and the social sciences. So, just as the Anthropocene dramatically highlights the close entanglement of culture and nature, it also brings to the fore the necessity of combining the humanities and the sciences.[xxv] We need knowledge of the planetary ecological system, a complex biophysical system of which human global society and its accelerated growth are an integral part – a joint task for the natural and social sciences and the humanities. We need knowledge of how transformations work and how innovations can be directed and then spread in society – likewise a joint task for science and the humanities. Here, I have particularly argued for a role of the history of science in this context. And we need orientation knowledge, we need to know where our journey goes, what our values are and what kind of society we strive for.[xxvi] And even to this latter domain, traditionally related to religion and clearly a topic for the humanities, science provides important contributions. The knowledge of our place in the material universe, the historization of nature and the evolution of humans as a part of that history, including the evolution of their sociality and cognitive capacities, are examples of the surplus knowledge of science to be applied in this context.

In all three cases – system, transformation and orientation knowledge – we need the cooperation of science and humanities, and sometimes even mergers between them. The development of these types of knowledge cannot be done in any *ad hoc* manner. We need institutions to develop them, and we need the participation of society at large in this process. The above-mentioned Max Planck Institute in Starnberg appears to have been such a place, and there were other places worldwide that were at least partially devoted to such aims. The Research Institute for Humanity and Nature in Kyoto, which hosted the workshop at which this contribution was first presented as a paper, is, as far as I understand, precisely a place where such interactions take place and such new knowledge is developed. It is through the transformation of science within such institutions – through reflection on and the communization of science – that a new relation between humanity and nature may emerge, not as a prerequisite, but as a consequence of a science for the Anthropocene.

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Notes

[i] A recent publication on the current state of the discussion is Zalasiewicz *et al.* (2019).

[ii] "We may speak of science if the goal of a certain social activity consists in elaborating the potentials of the material tools of mental labor, which are otherwise used in the planning of work, apart from such goals [and] solely for the purpose of gaining knowledge about the possible outcome" (Damerow & Lefèvre, 1996, p. 398).

[iii] For a brief discussion of the origins of the sexagesimal place value system and its conceptual consequences, see Damerow (2016), in particular pp. 109–112.

[iv] See Høyrup (1994, pp. 45–87), for instance. On pp. 79–84, the chapter discusses the particular character of Old Babylonian mathematics.

[v] For the *Suanshu shu*, see Cullen (2004); for the *Jiuzhang suanshu*, see Chemla and Guo (2004). For a stage model of the historical development of the number concept, see Damerow (2007).

[vi] The term 'Lysenkoism' refers to the ideologically guided approach to agricultural science in the mid-twentieth-century Soviet Union pursued by Trofim Lysenko and supported by Joseph Stalin. Lysenko rejected the concept of natural selection and other central concepts of genetics and instead propagated agricultural policies built on Lamarckism. Dissenting scientists were criticized as 'bourgeois', prosecuted and, in many cases, executed. Lysenko's doctrine could not be corroborated empirically and the agricultural policies based on it failed.

[vii] This interpretation is suggested by Graham (1978), a comprehensive translation, analysis and interpretation of the so-called dialectical chapters of Later Mohism, and Graham (1989), which places the Mohists in a broad history of early Chinese thinking.

[viii] "The most important thing about this excerpt on the lever and balance is that it shows that the Mohists must have been essentially in possession of the whole theory of equilibria as stated by Archimedes" (Needham, 1962, p. 23).

[ix] For the Mohist sections on mechanics, this argument has been made by Renn and Schemmel (2006). A comprehensive new translation and interpretation of the scientific sections in the *Mohist Canon* by Boltz and Schemmel is in preparation.

[x] See Boltz and Schemmel (2016, p. 143). Henderson (2010, p. 182) describes it as a "recent consensus of scholars working in the field" that "correlative cosmology was not highly developed or even systematized before the third century BC, with the *Lüshi chunqiu* (Master Lü's Spring and Autumn Annals) (c. 239 BC) being the first extant text to lay out systems of correspondence in great detail."

[xi] For a substantial criticism of such simplifying views of Chinese thinking on nature, see Roetz (2010), who connects the philosophical discussion with the problem of ecological practice and concludes: "There is no simple message from the East as to how to solve the ecological crisis. Ecological thinking has not merely to overcome a 'Western' mentality of the subjugation of nature. The problem is at the very core of human civilization, China being no exception" (Roetz, 2010, p. 217). For criticism of this simplified way of thinking about nature in Japanese thought, see Thomas (2001).

[xii] This is how Schwartz (1985, p. 351) epitomizes such a way of thinking, which he relates to the influence of Marcel Granet's writings and his *La pensée chinoise* in particular (Granet, 1934).

[xiii] This point is laid out in detail in Lefèvre (1978).

[xiv] The following argument has first been made in Renn and Schemmel (2017).

[xv] The question is discussed, for instance, in Graham (1973).

[xvi] On the transfer by Jesuits of scientific knowledge to China, see Schemmel (2012) and the literature cited therein.

[xvii] On the early seventeenth-century translation of Euclid's *Elements* into Chinese, see Engelfriet (1998).

[xviii] See Schemmel (2008). Schemmel (2006) provides a condensed version of the argument.

[xix] 'Forman's thesis' refers to Paul Forman's famous but controversial claim of an influence of certain aspects of the culture of Weimar Germany on the interpretation and acceptance of quantum theory (Forman, 1971).

[xx] See, in particular, Pomeranz (2000), which is a book-long discussion of this question. Interestingly, science and the knowledge economy do not figure prominently in Pomeranz's argument.

[xxi] See the overview of these early developments in Hu (2005, pp. 14–46).

[xxii] Jürgen Habermas (1989, p. 88) uses these phrases in his article 'Technology and Science as "Ideology"' – originally published in 1969 and dedicated to Herbert Marcuse – in a critique of certain ideas of Marcuse: "Marcuse has in mind an alternative attitude to nature, but it does not admit of the idea of a New Technology" (Habermas, 1989, pp. 87–88).

[xxiii] These questions are closely related to the discussion on ways to treat scientific knowledge as a global common; see, for instance, Nonini (2006).

[xxiv] Apart from an English abstract, this publication is in German. A later collection in English of contributions concerning the central concept of the 'finalization' of science can be found in Schäfer and Böhme (1983).

[xxv] The need to overcome disciplinary boundaries, in particular between the sciences and the humanities, has extensively been argued for in van der Leeuw (2020).
[xxvi] For the distinction between system, transformation and orientation knowledge, see Renn (2020, p. 385), and the references given therein, in particular Pohl and Hirsch Hadorn (2007).

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