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Chapter 1

History of Science in the Anthropocene

Anybody who does not earnestly wish that all humanity is well, therefore abuses it. But he is not even a true friend of himself, if he wishes to live as a healthy man among the sick, as a wise man among the dumb, as a good man among the bad, or as a happy man among the miserable.

—JOHANN AMOS COMENIUS, *Pampaedia*

Wherever the problem of knowledge does not appear at the *beginning* of the consideration, it has already been robbed of its true force. The decisive achievement of modern philosophy is that it no longer regards knowledge as a question among others, one that can be treated and resolved incidentally on the basis of other systematic presuppositions, that it has learnt to understand knowledge as the creative fundamental force in the construction of the totality of intellectual and ethical culture.

—ERNST CASSIRER, "From the Introduction to the First Edition of *The Problem of Knowledge in Modern Philosophy and Science*"

Stormy Weather

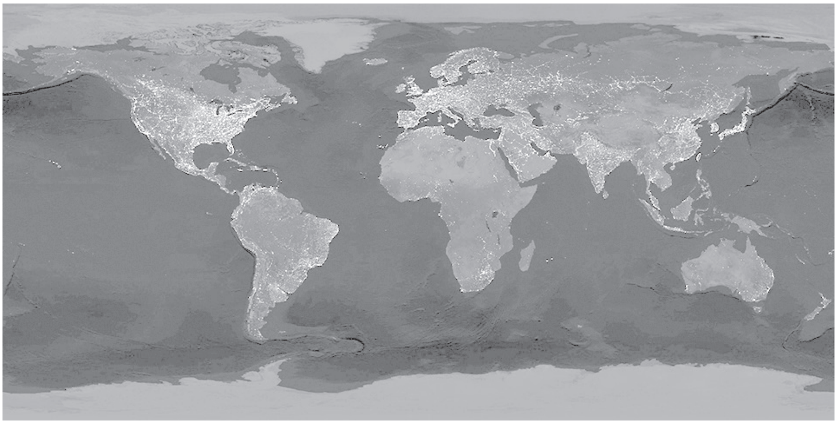
Humans have changed the planet.[1] Actually, humans have drastically changed the planet, with dramatic consequences. Nearly no untouched nature remains.[2] A large part of the earth's surface not covered by ice has been transformed. The polar ice is melting, the water level of the oceans is rising, and coastal and marine habitats are undergoing massive changes. More than half of the planet's freshwater is being exploited by humans. Oceans are being acidified and contaminated by aquacultures. Agricultural soil is being degraded. Beneath the surface, the earth is being altered by mines and drilling. The construction of thousands of dams and extensive deforestation massively affect water circulation and erosion rates and thus the evolution and geographical spread of numerous species. The loss of biodiversity is greater by orders of magnitude than it would be without human intervention. On average, at least every third nitrogen atom in our bodies has been once processed by the fertilizer industry. Most of the biomass of all living mammals is constituted by humans and domesticated animals.

Through energy-intensive chemical processes, humans use and create functional materials (which are rare under natural conditions), and brought them into wide circulation. Among these are elemental aluminum, lead, cadmium, and mercury, fly ash residues from the high-temperature combustion of coal and oil, and also concrete, plastic, and other man-made materials, many of them displaying properties alien to the natural world. Plutonium from atmospheric nuclear testing will persist in the sedimentary record for the next several hundred thousand years while it decays into uranium and then into lead. We are directly measuring the highest atmospheric concentrations of the greenhouse gases carbon dioxide and methane in at least eight hundred thousand years, and indirectly, in at least four million years. The figures are rising steeply. Even if the use of fossil energy resources were to stop immediately, it would take thousands of years before that concentration sank to preindustrial levels.

Some changes have occurred at a much brisker pace than natural processes. The present concentration of carbon dioxide has been reached at a rate at least ten, and possibly one hundred times faster than increases at any time during the previous 420,000 years. Simultaneously, new diseases have spread via carriers with rapid life cycles that allow them to adapt quickly to the new conditions. How quickly will human societies be able to adapt to the same? The ongoing changes will affect, in any case, different parts of the globe in different ways, and the global nature of these changes will not always be easy to recognize for those who suffer from them. With floods increasingly menacing low-lying cities near large bodies of water, new forms of gentrification emerge, raising the prices of dry and secure locations and displacing the poor. Previously fertile farmlands dry out because of drought, inciting allocation battles and migrations to richer nations. Developed countries may actually appear to benefit from climate change, while developing countries suffer—but ultimately everyone will lose. There will be no escape, not even for the rich.

In short, the planet is changing, with irreversible consequences. The human species has mushroomed all over the planet. Humans have massively intervened in various Earth system cycles, such as the carbon cycle, causing climate change, as well as the water, nitrogen, phosphorus, and sulphur cycles, all of which are fundamental to life on Earth. Humanity has affected the energy balance at the earth's surface, resulting in the transition of our planet into a new stage. Humanity does not act against the backdrop of an unchangeable nature; it is deeply woven into its very fabric, shaping both its imminent and distant future. For all of humanity's interventions in planetary cycles, it is still part of the biosphere, with no power to transcend it. We are not outside observers!

The fundamental revision of our understanding of the state of this planet may only be compared to the upheaval of our physical conceptions of space and time in the wake of Einstein's theories of relativity. In classical physics, space and time seemed to be the rigid stage on which world events were taking place. According to Einstein's theory, in contrast, this stage is no immutable framework but is itself part of the drama; there is no absolute distinction between the actors and the scenery. Space and time do not remain in the background of physical processes but rather take part in them. The new reality of the planet confronts us with a similarly radical need to rethink our situation: we are not living in a stable environment that simply serves as a stage and resource for our actions; rather, we are



1.1. Artificial light on Earth. The brightest areas are the most urbanized but not necessarily the most populated. Some remain unlit, such as the jungles of Africa and South America or the deserts of Arabia and Mongolia, even though lights begin to appear there as well. Created in 2006 with data from the US Defense Meteorological Satellite Program's Operational Linescan System. Wikimedia Commons.

all actors in a comprehensive drama in which humans and the nonhuman world take part equally.

In the year 2000, Nobel Prize winner and discoverer of the mechanism responsible for the hole in the ozone layer Paul Crutzen felt uneasy with the official account of the state of the planet, according to which we are presently living in the "Holocene" epoch. Geologists have a sophisticated system to classify the enormous time span of the earth's history into intervals. *Holocene* means "entirely recent" and is the second epoch of the so-called Quaternary period, after the Pleistocene. However strange it may sound, the Quaternary is actually an Ice Age that began ca. 2.6 million years ago; more precisely, the Quaternary is characterized by a back-and-forth of polar ice. The Holocene is an interglacial period in which the ice retreats. It began 11,700 years ago, and its climatic conditions have been unusually stable ever since.[3] Crutzen was participating in a conference on Earth system science outside Mexico City when he was struck by a sudden dislike for the Holocene description, which seemed to utterly belittle the human impact on the Earth system. He told the delegates to stop using the term "Holocene" and, while speaking, searched for a better one: "We're not in the Holocene anymore. We're in the . . . the . . . the Anthropocene!"[4]

As it turned out, the term had been used by the limnologist Eugene F. Stoermer since the 1980s.[5] Similar terms have been introduced independently by several scientists. In particular, the concept of a "noosphere" had been introduced and developed by Vladimir Vernadsky, Édouard Le Roy, and Teilhard de Chardin. They conceptualized, albeit in very different terms, humanity as a powerful geologic force and also considered the ethical implications of this assessment.[6] The roots of the idea of humanity as a planetary force go back even to the eighteenth century, when the French naturalist Comte de Buffon (Georges-Louis Leclerc) remarked that "the entire face of the Earth bears the imprint of human power."[7] Its current centrality for a broad discourse on planetary changes and humanity's role in them is, however, connected with that crucial moment in the year 2000. Crutzen himself and scholars of many disciplines have since controversially discussed the Anthropocene and its meaning in understanding humanity's predicament, but also its viability as a geologic time period.[8] The stratigraphic existence and onset is currently being examined by the Anthropocene Working Group (AWG), an interdisciplinary body of geoscientists, which will submit a formal proposal to the Subcommission on Quaternary Stratigraphy. This subcommission, in turn, reports to the International Commission on Stratigraphy (itself responsible to the International Union of Geological Sciences), where it will be ratified by its Executive Committee. To date, the AWG's recommendation is that a new epoch exists, functionally and stratigraphically distinct from the Holocene, and that its boundary layer should be placed around the mid-twentieth century.[9] Whatever the final decision of the geological experts may be (at each step of the formal procedure a majority is required with at least 60 percent of the votes in favor), the concept of the Anthropocene has opened our eyes to a fundamentally altered global environment and the fact that humanity has changed the planet to a degree comparable to geologic forces.

Given the massive impact of human intervention on the planetary environment, the traditional line between nature and culture has become problematic. We are living in an "anthropological nature" resulting from our own interventions.[10] Furthermore, the timescale of human history has become intrinsically meshed with the geologic timescale. Our economic metabolism feeds on fossil energy, consuming within a time span of hundreds of years resources that have been created over hundreds of millions of years. Just as geologic time is turned into historical time, our impact as a geologic force turns human history into a significant part of geologic history.[11]

Who Is Destroying Our Planet?

The question of whether and when the Anthropocene began is still debated. What is clear is that the transformative power of humanity is based on knowledge, accumulated and implemented over generations and ever more quickly since the Scientific Revolution, the Industrial Revolution, and the so-called Great Acceleration beginning in the 1950s.[12] What has also accumulated, however, are the unintended consequences of human activity. Nobody seriously intended to destroy the planet, though many have nevertheless taken bold risks to do just that. Some consciously decided not to act against evident dangers and simply continued with their destructive profit-making ventures. Specifically, science and technology have contributed much to bring us into this situation, and were not unaware of the problematic consequences. Global capitalism, industrialization, traffic, and population growth would not be possible without the advances of science and technology.[13] They have catapulted us from the age of horse-drawn plows and carriages to the age of industrialized agriculture and self-driving cars, and they have blessed us with the unequally distributed benefits of modern medicine. But along with their progress, science and technology have generated unintended consequences such as uncontrolled growth, the ruthless exploitation of natural resources, and a rapid increase of the greenhouse emissions that are changing the global climate.[14] Humans are now able to send missions into interplanetary space, but they have not yet found a way to protect billions from poverty or starvation, to contain wars, or to cope with all the other challenges of the Anthropocene for humanity as a whole. True, these are political and economic questions, not just questions of knowledge, but they are also questions of knowledge and of science—they are, as I shall say, "epistemic questions."

Take, for example, the transformation of global energy systems from fossil and nuclear resources to renewable energy. This transformation will be crucial if climate change is to be contained within limits that appear to be manageable today.[15] Its success will depend on a lifestyle change, but also on solutions to many unresolved scientific, infrastructural, and technical questions, such as problems with the storage and transport of renewable energies. New knowledge will also be required to deal with the social, economic, and political processes involved in this transformation. Past experience has shown that technical or economic solutions that have proven applicable to a specific geographic site under specific circumstances may not be easily transferable to another.

All future energy supply solutions should be designed and verified in light of their impact on both local and global geologic, physico-chemical, biological, and societal schemes. This will require competency in natural science, technology, the social sciences, and the humanities, as well as local insights on an unprecedented scale. It is as yet unclear by which political and societal processes an energy infrastructure can be transformed in harmony or in conflict with political and economic interests. This will likely require the active participation of a broad, well-informed public, but also new knowledge about the societal processes associated with such changes. Energy transformation is thus a good example of how we must rethink technical transformations as societal transformations and societal transformations as knowledge transformations. However, what matters in the end is that we stop burning fossil fuels, rapidly enough to perhaps mitigate the most catastrophic consequences of further climate change.

In view of this precarious situation, global inter- and transdisciplinary cooperation in science and education have become more urgent than ever. But the international competitiveness inherent in globalization may also have problematic consequences for the organization of research and education—in particular the fragmentation, mainstreaming, conformity, and commercialization of knowledge. In general, the way science and technology are employed depends on the structure of a society, on the way it makes or does not make use of knowledge, on the relation between power and knowledge therein, and on the question of whether and to what extent unintended consequences are taken into account.

Every society has its own "knowledge economy." It comprises the ensemble of its social institutions and processes producing and reproducing the knowledge at its disposal, and, in particular, the knowledge on which its reproduction as a society relies. The action potential of a society (for instance, its reaction to external challenges) depends on its knowledge economy and, in particular, on the societal structures that enable and limit its further exploration of knowledge. While knowledge enables individuals to plan their actions and consider the results, a society cannot "think" but can only anticipate the consequences of its actions within its economy of knowledge. The ability of global human society to cope with the challenges of the Anthropocene will therefore critically depend on the future development of its knowledge economy.

At the beginning of the twenty-first century, the prevailing mechanisms for governing science encourage the production of more and more publications representing ever-smaller units of information. The shattering of scientific knowledge into small contributions has led to a growing fragmentation of science, possibly to the exclusion of insights that could be relevant to addressing the challenges of the Anthropocene—challenges that, by their very nature, cannot be subdivided into disciplinary siloes.

Driven by economic globalization processes, national science policies are increasingly oriented toward international competitiveness, potentially limiting the scope of curiosity-driven research and running the risk of overlooking opportunities that are off the beaten track. No major society today can seemingly permit itself not to foster and regulate its science and education systems according to globalized models. Global competition forces science to cope with economic globalization and its consequences, for example, by feeding into national innovation systems (public and private), but also by conforming to globalized models of the knowledge economy, including both education and research. Incentives are being introduced both on the individual level (i.e., by the management of research according to contractually specified objectives) and on the institutional level (i.e., by implementing quasi-markets through an increasing competition for third-party funding, and through a shift from long-term institutional financial support to short- and mid-term program-oriented financial support).

The dynamics of international competition strengthen globalized models of science and education and the tendency toward a fragmentation of knowledge. The ensuing globalization of science tends to replace reflection with competitiveness and to downplay the role of specific contexts and local knowledge in favor of principles of science organization that are assumed to be of global and even universal validity. Yet it is through this perspective that most societies have come to view their problems, often disregarding the potential inherent in their own particular traditions or in opportunities for adapting those principles—opportunities that sometimes only come with a decoupling from global trends and adapting science policy to local conditions.

The fragmentation of scientific knowledge that is accompanying its globalization becomes particularly problematic when considering the challenges of the Anthropocene. Dealing with these challenges, scientific fields including atmospheric science, Earth system research, oceanography, evolutionary biology, environmental science, epidemiology, and space-based science, as well as sociology, political science, economics, computer science, history, cultural studies, and psychology need to cooperate in forms that transcend not only disciplinary boundaries but perhaps also traditional forms of scientific organization, knowledge production, and education. Given the unpredictability and inevitable serendipity of innovation, it would be shortsighted to bend the practice of science primarily toward the challenges at hand. It would be equally risky, on the other hand, to maintain the self-inflicted fragmentation characteristic of the current knowledge economy, as driven by the competition for real and "symbolic" capital.[16]

Humans intervene in the Earth system without realizing how that system's innate character may influence the consequences of the interventions. In order to understand these consequences, one also has to take into account the entanglement of human and earth history, as well as the potential, whether creative or destructive, of human thinking. Necessary to addressing the global challenges of the Anthropocene and the inseparability of their natural and cultural components is therefore an integrative perspective on knowledge that includes not only the physical science of the Earth system but also the interpretative and critical disciplines of the humanities.

Unwisely, we have left the astonishingly stable state of the Holocene, which has shaped our culture and our ways of thinking. The Anthropocene may be a contrary state of the Earth system, but it is not necessarily the demise of humanity—we simply do not yet know what it holds in store for us. By popping our "holocenic bubble," we are not withdrawing from a static system; we are intervening within a system that is itself highly dynamic. We are performing a global experiment on a system that is already changing itself; our interventions therefore introduce second-order changes. As a consequence, we make ourselves ever more dependent on our understanding of this complex dynamic system and our interactions with it. This understanding is itself not static but subject to a dynamical evolution.

Understanding the dynamics of knowledge is therefore crucial for our future in the Anthropocene. Both knowledge and changes in the environment accumulate across generations in long-term processes—and not necessarily in such a way that the survival of human culture in any recognizable sense is guaranteed.

The World as a Problem of Knowledge

But what is knowledge? Individual knowledge is based on encoding experiences, enabling individuals to solve problems as part of their adaptive behavior. It is rooted in the ability to anticipate actions and their results, and can be corrected in response to consequences, since we can think or "reflect" on our experiences. Due to the dependence of knowledge on prior experience, its predictive power is in principle limited. On the other hand, knowledge can be mentally stored in the form of cognitive structures and repurposed for new goals.

Knowledge has not only mental, but also social and material dimensions. It can be stored, shared, and passed on from individual to individual and across generations with the help of "external representations," such as writing or symbol systems, which are part of the material culture of a society. Material culture not only determines horizons of possible action and forms of social organization, but also a horizon of thinking. The emergence of the concept of energy, for instance, only became possible once actual transformations of motive power (e.g., the replacement of human force by wind or waterpower, and later by the steam engine) emerged historically as material practices. Similarly, twentieth-century cybernetics and control theory were preceded by practical experiences with such feedback mechanisms as James Watt's centrifugal governor, which regulated his pioneering steam engine.[17]

Many scientists would argue that knowledge is philosophically neutral, in that it can be put to good or bad use. This is at least the more traditional position, which shifts the responsibility for the impact of science away from the experts producing new knowledge. By this reckoning, it is not the scientists' responsibility if, for instance, a new chemical substance they develop is employed against civilians in war.[18]

But can we really let scientists (and anybody else who produces knowledge) off the hook so easily, allowing them to shirk all responsibility? Is there even perhaps a perspective from which we may consider the abuse of knowledge to be an expression of ignorance? This point of view certainly requires a broader concept of knowledge than that which is usually employed in academic discourse.

Such a concept of knowledge would also have to contribute to an understanding of what is or is not morally just under particular circumstances, thus informing ethical decisions and political actions. Is it conceivable to arrive at such an encompassing notion of knowledge, a notion that would also facilitate, for instance, the insights that enabled a Martin Luther King Jr. or Nelson Mandela to change the world for the better? This would then constitute a radical answer to the radical neoliberal ideology claiming that when problems cannot be resolved with the help of market forces, the answer is not to limit them but to demand even fewer market constraints. In contrast, I argue here that we should embrace the possibility of rethinking all of our challenges as challenges of knowledge, and that when our knowledge does not suffice, we require more and perhaps different knowledge (e.g., about the functioning of markets).

As a society, we may locally and temporarily establish whatever values and norms we like, and then produce, share, and consume the kind of knowledge that our knowledge economy is capable of generating. Ultimately, however, with growing global connectivity and the planetary impact of our collective actions in the Anthropocene, the totality of our accumulated experiences will determine the fate of the human species, as it does already for many other ones.[19] Some seemingly self-evident or apparently desirable social, economic, and political structures, or even the established norms for social behavior and knowledge production may eventually lead to the demise of human culture as we know it; these would then be unmasked as unsuitable societal structures and imprudent moral and epistemic standards. This perspective suggests that a justification of universal values and knowledge need not involve any form of transcendence, only acceptance of the principle that the highest value is the survival and thriving of the human race, perhaps combined with the sobering but liberating insight that human life is ultimately nothing but a purpose unto itself.

Let us return to our question: According to a tradition going back to the German philosopher Immanuel Kant, the real is not given to us, but put to us by way of a riddle.[20] What does the world look like if one considers its problems as problems of knowledge, and how does one have to conceive of knowledge in order to make this perspective possible? In our individual lives, we experience our ability to change things. We also learn to anticipate behavior and that we are often wrong. Yet we cannot imagine our lives without setting goals, planning, and thinking about our actions, and the experience and the knowledge this provides. Our thinking and our knowledge are major factors in determining what we do with our lives. Our collective lives, the histories of human societies, are also unimaginable without human drives and thinking, without collective experiences, beliefs, feelings, and knowledge.

Any historical account helpful in addressing the challenges of the Anthropocene should therefore do justice to the evident fact that humans are actors whose actions are not just determined by their natural, social, and cultural environments, by their economic, political, or religious interests, or by their drives and passions, but also by their thinking, and in particular by what they actually know about the world and themselves, and by how they know and share it, as well as by the way in which they make use of their knowledge. The presupposition of such an account, however, cannot be that humans own this force as a property naturally (or divinely) granted to them; the challenge is rather to understand how their autonomy as actors could and can be gained through knowledge, if at all. In this way, one might also gain a better understanding of what is usually referred to as human freedom, which is in fact inseparable from our incurably limited and precarious human capacity to understand and judge our predicament, and to conceive of actions to change and even improve it—in short, from the human capacity to think and to use knowledge.

There is a long history of attempts to define knowledge. A review of this discussion would merit a book of its own. For a history of knowledge, and for a general history to which knowledge is central, one might begin with the categories used by the historical actors themselves. Actors' categories certainly offer important clues about the role they ascribed to knowledge in their historical contexts, but these categories do not necessarily cover even their own practices. Such categories also make it difficult to compare different actors and periods, and they hardly live up to the standards that we require today from analytical concepts that allow us to understand historical processes and their dynamics.

Definitions of knowledge that have come from nonhistorical studies, on the other hand, such as the understanding of knowledge in philosophy or the cognitive sciences, may lead to anachronisms, since these intellectual pursuits have no empirical basis on which to judge how knowledge may change in history. Investigating knowledge in history can thus be neither a journey on which one embarks without any conceptual equipment, hoping to pick up whatever the historical actors have left behind, nor a voyage undertaken with one-size-fits-all rigging. A history of knowledge, with knowledge itself as an analytical category, will rather be an exploratory venture that promises new insights not only into historical developments but also into the nature of knowledge itself.

Between the History of Science and the History of Knowledge

One key question is whether and how knowledge evolves in history. Clearly, there is some degree of accumulation through the transmission of knowledge from one generation to the next, but there are also immense losses of knowledge, major failures, and profound transformations of knowledge systems, even when they are not "revolutions" in the sense of sudden ruptures. Investigations limited to specific historical case studies and categories of actors suggest a kaleidoscopic picture in which variety is the only recognizable overall pattern. There is, however, one strand in the history of knowledge to which a developmental logic has been traditionally ascribed: the history of science, which has, for a long time, been conceived as being governed by a logic of progress, occasionally interrupted by relapses and errors.[21] But when considering the history of science within the broader context of a history of knowledge, one wonders whether this notion of its development is an exception or an illusion.[22] This question is, in any case, closely related to the questions of whether society at large advances with the progress of science and whether science depends on cultural contexts.

The self-image of science as a paradigm of progress has accompanied modern science since its inception. For Francis Bacon, only the progress of the sciences, the *progressus scientiarium*, is temporally unlimited, while political improvements are locally and historically confined, and mostly involve violence and chaos. Inventions, on the other hand, bring happiness without inflicting injustice or suffering.[23] During the Enlightenment, the mathematician Marquis de Condorcet linked scientific progress programmatically with social emancipation, aiming at the elimination of inequality through knowledge dissemination and education.[24] But even Condorcet's ideas threatened to end up in a comprehensive rationalization of all of life and thence in a technocratically engineered society. Alexander von Humboldt and his fellow scientists were also convinced that technological innovation, promoted by the sciences, improved the common good.[25] But in the age of the Industrial Revolution, it became ever more evident that the advancements of science and technology do not automatically lead to the progress of society as a whole, as the fruits of technological advances were clearly being distributed unevenly in the emerging capitalist societies, while machinery was used to extract ever greater labor value from workers.

Yet the hope that a link between scientific, technological, and societal progress could nevertheless be established was not abandoned. In the wake of the triumph of Darwin's theory of evolution, some thinkers even declared progress to be a natural law governing both biological and societal evolution.[26] Such hopes were challenged, however, by the catastrophes of the twentieth century.

Whatever relation they perceive between scientific and societal progress, most scientists distinguish their activity from all other cultural expressions of our species primarily by one property—the "cumulative" character of science. Almost all scientists are personally convinced that they can see farther than their predecessors because they can build on their achievements. Scientific progress is similarly taken for granted in traditional studies of the history of science. The underlying image is a kind of relay race of titans, passing the baton of ingenious ideas one to the next—a very undeveloped idea of an economy of knowledge indeed. The history of science thus becomes a chronicle of success, a who, what, when, and where of progress.

In actuality, these questions are better suited to investigating professional sports than science. They do not take into account the fact that the various "sports" of science (i.e., the fields of investigation) have themselves always been subject to redefinition. The history of science is traditionally written from the present backward. Thus, whatever is required to tell a success story of how the present came into being belongs to the history of science; cases that are seen as embarrassing, such as astrology or alchemy, belong to the "prehistory" of science.

Current studies in the history of science tend to question the scientific claim to progress, because such a stance seems incompatible with the extent to which science shares the fallibility of other human endeavors. As a result, science no longer appears distinguishable from other cultural practices. It has ceased to be a paradigm of universal rationality and is presented instead as one more object of study for cultural history or social anthropology. Even the most fundamental aspects of the classical image of science—proof, experimentation, data, objectivity, rationality—have proven to be deeply historical in their nature.[27] On the one hand, this insight has turned out to be liberating, at least for the historiography of science, which now more than ever has begun to take into account the cultural contexts of the scientific enterprise. On the other hand, science no longer offers, as a consequence of this view, a model of rationality that could be applied to other domains of human life.[28]

These more recent studies have opened up a new perspective on the study of the history of science, which is increasingly turning into a history of culture that includes science among other forms of knowledge. These other forms of knowledge include not only academic practices, but also the production and reproduction of knowledge far away from traditional academic settings—in artisanal and artistic practices, for instance, or even in the household and the family.

In traditional terms, the Scientific Revolution of the early modern period was seen as giving rise to modern science not only through specific discoveries but also by establishing a general scientific method, consisting in the formulation of hypotheses that are then tested by experimentation or observation. Modern science and the scientific method were allegedly developed in Europe, first in astronomy and physics, and from there conquered the world of knowledge, as well as the geographical world. Even the traditional account, however, concedes that some of this expansion was achieved only by force, by trying to impose the laws of mechanics on all science, for instance, or by the colonial expansion of Western science, often accompanied by the violent suppression of other forms of thinking.

The traditional argument was that scientific knowledge, wherever it came from, had a quality unique from all previous forms of knowledge. Today, however, some historians of science do not acknowledge a distinction between the validity of scientific knowledge and its historical origins. They no longer see the Scientific Revolution, for example, as a historical breakthrough that has fundamentally changed the practice of knowledge generation and led to the establishment, once and for all, of a scientific method.

Much of the knowledge that became relevant during the Scientific Revolution was the practical knowledge of artisans, engineers, physicians, and alchemists. It was by studying and transforming this kind of knowledge (which dealt, for instance, with the motion of projectiles in ballistics or with the transformation of materials in metallurgy) that contemporary scientists such as Galileo made their great discoveries.[29]

Thus, Galileo opens his final major publication, the *Discorsi* of 1638,[30] which lays the foundations for classical mechanics, with a eulogy to the artisans of the Venetian Arsenal, one of the greatest dockyards of his time.[31] The book is written in dialogue form and begins with a statement by the author's spokesman, Salviati, praising the expertise of the master builders:

> SALVIATI: Frequent experience of your famous arsenal, my Venetian friends, seems to me to open a large field to speculative minds for philosophizing, and particularly in that area which is called mechanics, inasmuch as every sort of instrument and machine is continually put in operation

> there. And among its great number of artisans there must be some who, through observations handed down by their predecessors as well as those which they attentively and continually make for themselves, are truly expert and whose reasoning is of the finest.

To which the other, like-minded interlocutor Sagredo responds, pointing out how much he himself has learned from these experts:

> SAGREDO: You are quite right. And since I am by nature curious, I frequent the place for my own diversion and to watch the activity of those whom we call "key men" [*Proti*] by reason of a certain preëminence that they have over the rest of the workmen. Talking with them has helped me many times in the investigation of the reason for effects that are not only remarkable, but also abstruse, and almost unthinkable.[32]

In short, other forms of knowledge, such as the practical knowledge of these artisans, have served as an important but traditionally neglected basis for scientific knowledge, so much so that one cannot truly appreciate the dynamics of the Scientific Revolution without taking them into account. Scientific knowledge is quite obviously connected with other fields of knowledge, and not only with the knowledge housed in theoretical traditions such as philosophy, but also with the practical knowledge of craftsmen and the intuitive knowledge that each of us must acquire in his or her individual development in order to cope with the material nature of the world.

Perhaps even more important, when broadening the vista to include other forms of knowledge, non-Western ways of dealing with knowledge come into view without being immediately gauged against the standards of established Western science. "On their own terms" is the slogan under which Chinese, Indian, and Islamic science are now being analyzed.[33] Similarly, the worldwide circulation of knowledge is now considered not just as a one-sided colonial or postcolonial diffusion process from a center to the periphery, but as an exchange of knowledge in which every side is active and in which knowledge is as much shaped by dissemination as by an active appropriation on the side of the "receivers."

In summary, such an inclusive perspective on knowledge has opened the door to a new understanding of the worldwide dynamics and history of scientific knowledge. It may even seem as though scientific knowledge has lost its place of privilege among other forms of knowledge. But this conclusion is premature. Clearly, there is knowledge outside the sciences. It is equally clear that scientific knowledge is not independent from the knowledge of other areas (nor from other factors, such as technology). It is indeed hardly possible to distinguish scientific knowledge from other forms of knowledge by epistemological criteria alone, or even with the help of a theory of science.

Nevertheless, from a historical perspective, it is generally possible to recognize science in various cultures and periods as a special form of knowledge whose character may, however, change with the historical context. Scientific knowledge involves not only theories but cultural practices consciously directed at the coinage of knowledge that can be transmitted from generation to generation. Scientific knowledge is accumulated and transmitted by "epistemic communities" dealing—often within dedicated educational institutions—with the preservation, improvement, and production of knowledge. Such knowledge is typically encoded using specific external representations, such as texts and instruments.

Scientific practice comprises forms of initiation, education, exploration, discourse, and transmission that are subject to historical change. Historically variable argumentative standards, control structures, and practices for the validation of knowledge all shape its accumulation and corrigibility, thus extending the learning and self-correcting aspects of individual knowledge to a societal institution. A lasting merit of the philosopher Karl Popper is having placed corrigibility at the center of a conception of science as an ever-incomplete quest for knowledge.[34] The specific form that scientific knowledge takes depends on the role a society assigns to knowledge, its "image of knowledge."[35]

Scientific knowledge first emerged in complex societies that created social spaces for exploring knowledge independently from immediate practical purposes. We may therefore speak of "science" whenever the potential inherent in the material or symbolic culture of a society is being explored for the primary sake of knowledge generation.[36] Nobody could have anticipated that human societies would eventually become dependent on such knowledge, a challenge made even greater by the intrinsically uncertain nature of scientific knowledge.

Science as a Golem

A cultural history of science that primarily focuses on specific case studies, while being unable to account for its long-term development, inevitably creates a highly fragmented picture. In this view, science dissolves into a plethora of localized and contextualized activities that are no longer distinguishable from other cultural practices.[37]

This picture can hardly do justice to the overwhelming societal, economic, and cultural significance of science in a globalized world. It has become a mark of political correctness to "provincialize" European or Western science as representing just one among many, equally justified points of view within global culture.[38] But well-meaning political correctness on the part of historians and philosophers can hardly compensate for the destruction of indigenous cultures, for the crimes and the genocides—in short, for the immense damage and abuses that have been committed in world history with the help of science or in the name of Western rationality.

Science may be compared to the golem of Jewish folklore, a being created from inanimate matter, then magically activated to perform useful services, albeit with the risk of becoming independent from, and even hostile to, its creator. As Harry Collins and Trevor Pinch put it, "Science is a golem. A golem is a creature of Jewish mythology. It is a humanoid made by man from clay and water, with incantations and spells. It is powerful. It grows a little more powerful every day. It will follow orders, do your work, and protect you from the ever threatening enemy. But it is clumsy and dangerous. Without control, a golem may destroy its masters with its flailing vigour."[39] The golem of science cannot, in any case, be tamed by underes-

1.2. Rabbi Loew brings the golem to life. Drawing by Laurent Taudin.

timating it, let alone by overestimating our own influence as its creators, witnesses, or critics. There cannot be any doubt: since the nineteenth century, science has dramatically changed the human condition in terms of energy provision and food production, through the introduction of new materials and new forms of transportation and communication, and with new pharmaceuticals and advances in medical care. Now the very survival of our culture in the Anthropocene may depend on the production of the appropriate scientific and technological knowledge.

Considered in this light, any doubts about the cumulative, self-accelerating character of the development of science may seem to be merely a matter of esoteric academic debate. Both believers in scientific progress and skeptics ultimately tend to be united on one point: scientific development is like a mighty, forward-striding golem whose pace establishes, for good or evil, the rhythm of modern industrial and postindustrial societies. Denying the substantial effects of science and technology on modern society amounts to reopening the debate on whether the earth is flat. It is, however, another matter to reconcile the striking impact of science with the complex and often difficult relationship between science and society. Equally challenging is the fact that scientific progress is hardly an automatism or necessity but merely a serendipity of human history.

How Does Knowledge Evolve?

How can radical change in scientific thought be reconciled with the retention and gradual expansion of the knowledge that has preceded it? And how are we to assess the evident existence *and* limits of scientific rationality—as well as its failure to serve as a model for societal progress at large? In this book, I shall show that none of this can be understood without taking into account that science never works in isolation but always as part of larger systems of knowledge, that these systems may profoundly change their structure in the course of history, and that such systems are part of the encompassing knowledge economy of any given society.

One example of a system of knowledge is the curriculum of the medieval university, with its faculties of theology, medicine, and jurisprudence, prepared for by prior study of the seven liberal arts. Another example is the modern ensemble of scientific disciplines. But systems of knowledge do not have to be rigidly organized conceptual systems or intellectual practices; in fact, they do not have to be very systematic at all. The knowledge needed to build a house or to tend a garden may also be conceived as a system of knowledge, composed of many different elements. These elements are not held together by a strict organizational principle, but rather constitute a heterogeneous "package of knowledge." The relations among the components of a system of knowledge may be semantic, as in a scientific theory; they may be institutional, as in a curriculum; or they may be practical, as in the example of a building project.

How can a history of knowledge systems be written that goes beyond a merely descriptive account and yet avoids the pitfalls of forcing this history into a logic of inevitable progress or reducing it to a mere chain of chance events without explanatory value? Here a comparison with natural history may be useful, not in the sense of striving for a narrative of Big History (with a capital *B*) but in the hope of learning from explanatory approaches developed in other fields.

Evolutionary explanations thrived in the nineteenth century, when scientists and philosophers such as Charles Darwin, Ernst Haeckel, Karl Marx, Ernst Mach, Ludwig Boltzmann, Pierre Duhem, Wilhelm Wundt, and many others did not hesitate to seek for connections linking the evolution of life with the evolution of human culture and thinking. In Marx's *Capital*, for instance, we read: "Darwin has interested us in the history of Nature's Technology, *i.e.*, in the formation of the organs of plants and animals, which organs serve as instruments of production for sustaining life. Does not the history of the productive organs of man, of organs that are the material basis of all social organization, deserve equal attention?"[40] In his *Panorama of the Nineteenth Century*, Dolf Sternberger characterized "evolution" as the magic word of the nineteenth century.[41] The Darwinian synthesis of biology and the modern synthesis of evolutionary biology remain evident in and central to today's scientific concerns. This is not the case for the history of science, in which discussions about the evolutionary character of science, knowledge, and culture scarcely play a role.[42]

My point is not to reduce history to biology or to identify a survival of the fittest in the history of knowledge. I rather suggest that we learn from the capacity of evolutionary theory to explain both the historical continuity and the unceasing innovation of life forms, which it does by integrating numerous subdisciplines of biology (from genetics and physiology to paleontology and ecology) within a single historical theory of development, while transforming these subdisciplines in the process. Can a similarly overarching, integrative, and explanatory framework be found for the history of knowledge as an integral part of cultural evolution?

Such an attempt cannot succeed by simply mimicking the biological scheme. Just as the biological theory of evolution was founded on the basis of specific insights into the mechanisms of biological change, an evolutionary account of knowledge has to start from a detailed analysis of the mechanisms of historical change in knowledge and their relation to culture and society. A historical theory of knowledge must similarly rely on a broad array of disciplines to be integrated under a novel perspective and thus to become vulnerable to profound reinterpretations themselves.

Since cultural evolution is ultimately grounded in biology, its greatest selective force is human survival. This ultimate selective force is, of course, mediated through—and buffered by—many layers of culture and society that themselves impose diverse proximate forces of selection on knowledge systems and cultural evolution. Such layers can hardly be anticipated from biological considerations alone. But cultural or social evolution has also been considered an evolutionary process in its own right. This idea goes back to the nineteenth century, to the time right after the appearance of Darwin's *Origin of Species*,[43] with thinkers such as William James and Ernst Mach. It has been revived since the 1980s, when authors such as Richard Dawkins, Luigi Cavalli-Sforza, Robert Boyd, and Peter Richerson began to exploit the mature formal apparatus that evolutionary theory had meanwhile developed (including sophisticated population genetics) to explain cultural phenomena in analogy to biological developments.[44]

In general, these attempts do not reduce culture to biology but rather emphasize parallels—such as the analogy between biological and cultural inheritance through learning processes—and then adopt methods and models from evolutionary theory, as well as from statistics and game theory, to explain cultural change or phylogenetic lineages (e.g., in the evolution of languages). Cultural selectionists thus assume two parallel inheritance systems, one genetic and one cultural. One way in which they are intertwined is "niche construction," which essentially provides a third inheritance system that may be characterized as ecological inheritance. Living beings change their environments, either through phenotypical or through cultural traits, while a changed environment in turn reshapes selective pressures. All three inheritance systems are coupled by feedback loops.[45]

The Heuristic Role of Evolution

It may be tempting to generalize this approach to an evolutionary account of knowledge by identifying different mechanisms of transmission and variability and then seeing how far biological analogies and tools can reach in providing insights into the "population dynamics" of knowledge. This is, however, not the approach followed here. I take biological evolution neither as an overarching process that includes and governs culture and its dynamics, nor as delivering, by analogy with biology, a theoretical framework for the analysis of cultural history that may claim a similarly integrative function for the humanities and social sciences as that which Darwin's theory claims for the life sciences. The former would disregard the autonomy of culture; the latter, the autonomy of cultural studies—both amounting to some form of reductionism.

Rather, I consider the evolutionary theory of biology as a standard of comparison for any historical theory coping with the long-term development of complex adaptive systems like human culture—beginning, however, with its own genuine insights gained through centuries of research within numerous disciplinary traditions. In other words, instead of matching concepts from the realm of cultural analysis (e.g., institution and power, memory and repression, learning and reflection) to an evolutionary framework that is by-and-large borrowed from biology, I take a bottom-up approach. Such an approach begins with concepts, theories, and in-depth investigations from the humanities and social sciences and tries to build an explanatory framework that captures the riches harbored by these investigations, nevertheless keeping in mind that an explanatory framework for human history should comply with some basic lessons learned from evolutionary theory in the life sciences.[46]

Among these lessons is the temporal directedness of the overall process and the asynchrony of particular developments, that is, the lack of a global uniformity of evolution. Evolutionary accounts do not imply "progress" in any traditional sense, and, typically, their outcomes are neither determined by their initial conditions nor by some final goal to be eventually reached—one might say they are neither deterministic nor teleological. In fact, modern biology has long renounced any idea of evolution as the triumphant progress toward the most "highly" developed forms of life, with humans as the crown of creation. Evolutionary theory insists, instead, on the global connectivity of the entire process in which life has unfolded on Earth, often hidden beneath the dazzling variety of local forms. In the history of culture and knowledge we are still far from such a global account.

Another lesson is that evolutionary processes not only allow for chance events to occur but allow them to have long-term effects. Evolutionary processes are path dependent in the sense that current developments depend on past events, even though past circumstances may no longer be relevant. Nevertheless, the unpredictability of future developments, the dependency of later developments on earlier ones, and the role of contingency in such processes in no way force us to resign ourselves to a merely descriptive or taxonomic account, nor to one that is simply a collection of local narratives. Evolutionary accounts do have explanatory potential, beginning with a realization of the sheer complexity that mechanisms for ensuring continuity may give rise to when combined with possibilities for variation and selection.

Evolutionary processes do not just react to external conditions but may also shape their own environments, thus becoming self-referential—this feature is addressed under the label of "niche construction" in evolutionary biology (e.g., beavers constructing their dams). This is obviously also characteristic of cultural evolution. Another striking feature of evolutionary theory that invites a comparison with the history of knowledge is the insight that forms of life that emerge later in evolution do not necessarily eliminate earlier forms of life. To the contrary, simple life forms such as bacteria are by far the most successful models that evolution has ever generated. In a sense, the same holds for the history of knowledge; complex forms of knowledge such as higher forms of mathematics hardly ever completely replace earlier forms such as simple counting techniques.

Evolutionary processes may give rise to convergence (as when eyes developed independently in multiple species)—a phenomenon familiar, for instance, from parallel discoveries in science. Biological evolution generally works with modular components, which are reshaped into building materials for new life forms, as when certain organs are repurposed for adaptation to a new environment. The repurposing of the material environment is a similarly important aspect of cultural evolution. The "horizon of possibilities" shaped by historically bestowed material conditions is always broader than the possibility actually realized at any given moment.[47]

Biological evolution involves genes and their expression in phenotypes, the latter being a subject of developmental biology. Without implying that one can simply transfer this structure by analogy to the realm of culture, it still seems that cultural evolution without a concept of knowledge and a theory of knowledge development would be rather like biological evolution without genes and developmental biology. Indeed, some even define culture in terms of knowledge acquired and socially transmitted in the context of a constructed niche.[48] The transmission of human culture in any case goes beyond the ecological inheritance system associated with niche construction mentioned above, and it involves social learning and the transmission of material artifacts and signs that are detached from their immediate contexts of usage and organized within holistic systems of knowledge.

An Alternative to *The Structure of Scientific Revolutions*

In the following, I sketch such a theory based on detailed historical studies pursued with some of these questions in mind. These studies also cover, in particular, some of the major so-called scientific revolutions: the emergence of classical mechanics in the early modern period, the so-called chemical revolution of the eighteenth century, and the relativity and quantum revolutions of the twentieth century. The basic mechanisms of knowledge evolution that have been identified cannot be reduced to analogies of mutation and selection in biological evolution. They are in fact much more context-dependent and are themselves subject to change in the course of history. There is no general scheme according to which a scientific transformation takes place, for example, according to the sequence of normal science, crisis, and paradigm shift hypothesized by Thomas S. Kuhn in his epochal book *The Structure of Scientific Revolutions*.[49] Still, Kuhn's scheme may serve as a useful foil for identifying the features of an evolutionary account of the history of knowledge by contrasting them with what has meanwhile become a widely popularized—and misleading—idea of the radical breaks associated with scientific transformations.

In short, I argue that major changes in systems of knowledge happen, but that these changes are typically long-term, protracted processes. They cannot be adequately understood without taking into account that knowledge has a layered structure involving the different types of knowledge that are shared within the knowledge economy of a society. It is because of this layered structure of scientific knowledge (which also comprises intuitive, practical, and technical knowledge) that untranslatability or "incommensurability" between scientific worldviews or "paradigms" is a less serious problem in the actual workings of science than is assumed in philosophical discussions. In fact, the notion of incommensurability belongs to the sense of theoretical concepts,[50] whereas the reference of individual concepts (instruments, phenomena, etc.) may remain unaltered irrespective of theoretical changes, thus enabling communication on the basis of other, more pragmatically oriented layers of knowledge.

External representations and embodiments of knowledge such as texts, instruments, or infrastructures serve as the backbone of the transmission of systems of knowledge, ensuring their long-term continuity. Systems of knowledge and their external embodiments are applied and explored by practitioners of knowledge such as the members of a scientific community, either within institutions dedicated to the generation of knowledge or in practical contexts. This exploration leads to the enrichment, extension, and gradual change of systems of knowledge. Furthermore, shared knowledge is always carried by individuals and is thus intrinsically variable. A body of knowledge is never uniquely defined and therefore requires interpretation; different individuals or groups may view it in different ways at times. These variations may become a source of controversy, which is itself a means to conceptual development.

The exploration of the inherent potential of the historically specific means for gaining knowledge thus gives rise to a variety of alternatives within a knowledge system, becoming a source of novelty. In an advanced state of the development of a knowledge system, these variations typically lead to internal tensions and contradictions, which may become the starting point for the reorganization of a system of knowledge or the branching off of a new one. Some of the most crucial steps in the growth of knowledge were indeed not based on the acquisition of new knowledge but rather on developing new ways of using what was already known.[51]

A Global Learning Process?

On this basis, I claim, one can build a history of science as part of a global history of knowledge—without forcing it into a logic of progress and without abandoning the attempt to account for the long-term accumulation of earth-changing knowledge, the accompanying losses and deficiencies, and the dependence of scientific rationality on chance constellations. But how could such a history contribute to answering the questions that we have begun with, in particular the question of what knowledge is required to address the challenges of the Anthropocene? For starters, it would demonstrate in what sense science is just one aspect of a highly fragmented but nevertheless inexorable global learning process in which humanity as a whole, over time, assembles knowledge with the potential for shaping the world. It would also illustrate the ways in which this potential is actually used and would finally demonstrate that science derives its power from being one late result of this global learning process.

When I speak of a global learning process, I again have the comparison to biological evolution in mind. The process as a whole displays the features of individual learning, like the functional adaptation of life forms to their environment—without, however, presupposing an intelligent subject, and without any assurance that such adaptations may not eventually lead to the demise of a species. (Indeed, there are many examples of runaway selection in evolutionary biology, leaving species dependent on a particular ecological niche that may then disappear.) Similarly, human history is evidently not guided by some form of global, collective subjectivity but rather by processes that operate primarily within local settings, albeit with ever more global entanglements and consequences.

Faced with the global challenges resulting from these consequences—such as the changes in the Earth system, of which climate change is perhaps the most visible—we might wish for such a collective subjectivity to emerge and facilitate rational solutions to global problems. Indeed, some advocates of sustainability policies argue in this way, favoring, for instance, measures of geoengineering managed by international expert communities or authorities standing in for an always rationally acting world government. While geoengineering may even become unavoidable as a last resort, the latter hope will likely remain as illusory as the hope for an explanation of the history of life by "intelligent design." Investigating the evolution of knowledge could help us, on the other hand, to conceive of more realistic options for addressing these challenges; it might teach us how new solutions can emerge bottom-up rather than top-down, from the global machinery of knowledge production.[52]

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