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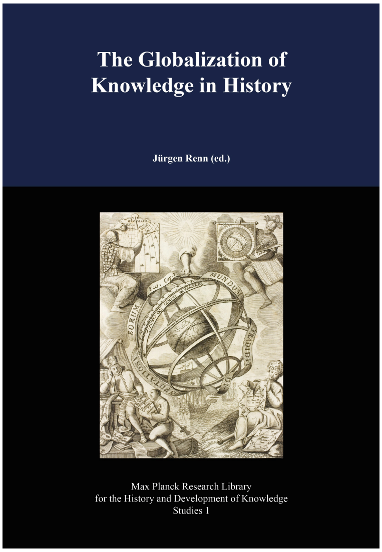

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Chapter 24
Survey: The Globalization of Modern Science

Jürgen Renn and Malcolm D. Hyman

24.1 A New Stage in the Globalization of Knowledge

Science may take on completely different forms in various cultural and historical contexts, but all of these forms of the human acquisition of knowledge share a general nature that lies in their exploration of the potential for innovation embodied in a given material culture.[1] This exploration, focusing on means rather than ends, occurs in a certain autonomy from the specific applications also given with this culture, through its tradition and concentrating on certain goals. Against the background of such a historical definition of science, the remarkable dual character it possesses, its durability and its fragility, becomes more understandable.[2]

The staying power of science and its relative stability are based on its roots in technology with which humanity reproduces its social systems. By contrast, science's lack of endurance and relative fragility lie in its dependency on the motivations prevailing in any given society. This fragility has been reduced more and more in recent centuries as science has gone from a voluntary occupation of small groups of elites to becoming a decisive element of global technology. However, this has made the remaining element of the fragility of science as a social enterprise particularly significant, because the very survival of humanity is determined to an increasing degree not only by the growth of science, but also by the direction and the conscious shaping of scientific progress.

Since the early modern period, the range of science has expanded dramatically, not so much because an alleged scientific method was exported to new domains of experience, but because ever new objects came into contact with the developing network of scientific knowledge and due to the intrinsic, cognitive dynamics of this network. Thus, newly discovered specimens from exploratory voyages, new technological devices, or social and behavioral phenomena that acquired practical relevance, such as population statistics, could constitute challenging objects for the existing scientific framework that eventually acquired global relevance.[3]

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[1] See (Damerow and Lefèvre 1981; Damerow 1996; Damerow and Lefèvre 1998).

[2] For the following, see (Renn 2003).

[3] For the notion of challenging object, see (Renn 2001; Büttner et al. 2004; Bertoloni Meli 2006; Büttner 2008; Valleriani 2010). For the role of exploratory voyages, see (Montesinos Sirera and Renn 2003). For the role of population statistics, see, for example, the Census of India which has been conducted since 1871 (Bayly 1999) and also (Gigerenzer et al. 1991).

Knowledge is globalized when it is in principle globally available and accessible. The globalization of knowledge today has reached a new stage: it has transformed the economy of knowledge radically, in ways that are comparable to the transformation in recent years of a monetary economy to a system in which local and global developments are coupled by almost instantaneous interactions. New potentials for the globalization of knowledge have emerged, such as the global system of science and the World Wide Web, offering immediate worldwide access to the knowledge produced within this system. Due to the increased mobility of people and things, research hubs and the human resources of science have become global assets. The migration of scientific knowledge is no longer characterized by the trajectories of individuals or by the dynamics of fellow traveling, but rather by global social patterns.[4]

Scientific knowledge is involved in global economic processes; it is embedded in global infrastructures and regulatory regimes and is part of global cultural products. Its relevance for political, economic and social systems is indicated by the fact that its mere existence may lead to global reactions in these systems, such as value changes in shares, or the occurrence of migrations, summits or even wars. The coupling of the globalization of science to economic globalization has led to a double economy of knowledge: commercial and open. Science itself has undergone massive expansion, alongside an increasing specialization and fragmentation of knowledge. But with the expansion of science new opportunities for knowledge integration and unification also emerged, as well as new perspectives from which knowledge can be judged and evaluated. The globalization of science has led to a self-organizing global distribution of intellectual labor, similar to but different from the global market, in which national institutional structures and epistemic traditions are losing autonomy.

First, we recapitulate the historical emergence of disciplinary science and its crisis in the age of classical science, that is, between the early modern period and the late nineteenth century, emphasizing the integration processes of scientific knowledge and the role of reflective thinking in these processes. Then we turn to the disintegration of knowledge and the globalization of science in the twentieth century, the age of the great wars. We conceptualize the globalization of modern science in terms of intrinsic and extrinsic processes and analyze the transformation of science as a result of its globalization. This discussion raises, in particular, the question of the autonomy of scientific knowledge with regard to its societal constraints. Turning to modes of reflection on globalized science in the age of liberalization, we observe that certain normative ideas about science, here described as the "classical image of science," have become obsolete in scientific practice but are still relevant for the interaction between science and society, limiting the potential of science to address global challenges.

These global challenges are then formulated as the emergence of "socioepistemic complexes," understood as large-scale societal structures, typically of global

[4]See chapter 9.

extent, enhancing the dependence of human society on the production of scientific knowledge. While social studies typically attempt to characterize the morphology of these complexes, they are here considered from the perspective of historical epistemology with regard to their role for human survival. The profound impact on the earth system of human interventions has been described by a geological metaphor referring to the current epoch as the "anthropocene" (Crutzen and Stoermer 2000; Costanza et al. 2007; Schwägerl 2010), thus proposing an image of knowledge adequate to the age of modern globalization. Here we rather insist on the evolutionary character of the development that has led to this stage, and in particular on the irrevocable role of scientific knowledge for its sustainability. Finally, a set of examples will be considered, illustrating the different forms in which socioepistemic evolution currently presents itself.

Evidently, globalization processes in science differ from discipline to discipline. While global big science takes place in cost- and labor-intensive research fields in the natural sciences and partly in the life sciences, the globalization of behavioral and social sciences are a result of the empirical turn and the confluence of national traditions. The globalization of knowledge is clearly not a one-way process of intended transmission, as the previous Parts have shown for other time periods. Also in modern science, knowledge becomes global both by processes of localization and delocalization. Knowledge is always bound to local conditions of its reproduction, and the problem of encounters between different knowledge systems embedded in different local conditions is a persistent feature of historical development. In a word, globalization is path dependent. Yet a convergence of various globalization processes may occur, in particular when they are coupled to the emergent challenges for human survival.

24.2 The Disciplinary Integration and Spread of Knowledge in the Age of Classical Science and European Imperialism

Ever since modern science reached maturity, that is, after the early modern period, its knowledge systems have been organized in terms of disciplinary structures.[5] These structures comprise theoretical frameworks and a material culture, as well as institutional settings that have turned out to be surprisingly stable and surprisingly mobile. In fact, the globalization of modern science has largely taken place in terms of a transfer of these knowledge systems. Everywhere in the world, universities have been set up and organized around these knowledge systems, with departments for mathematics, physics, chemistry, biology, and so on, and with comparable curricula.[6] This astonishing uniformity is not just a remnant of imperialism and colonialism; it is not primarily due to a dominating intellectual culture of rationality, nor is it simply a functionalist response of societies to deal with intellectual challenges to which there would not be any alternative.

[5] See (Stichweh 1984; Damerow and Lefèvre 1998).
[6] See chapters 18 and 25, and the discussion in (Osterhammel 2009, 1132–1139).

Rather, the existing scientific disciplines represent historically contingent systems of knowledge, resulting from a long history of knowledge integration and reorganization that has made it possible to condense a broad range of experiences in terms of a few core concepts, models, methods, technologies and institutional setups for each field. It is this condensation of knowledge that accounts for the high degree of autonomy of the disciplines with regard to specific local contexts, giving modern science the appearance of universal validity. This condensation makes it, at the same time, difficult to realize the implicit context-dependence of modern science, which is inherited from its contingent history but obliterated in its trajectory of "recursive blindness," that is, of ways in which prior knowledge becomes opaque with the accretion of new knowledge. This blindness accounts, at the same time, for the intrinsic difficulty of modern science and its protagonists to reflect on the contexts of its implementation.

The role of contingency in knowledge integration becomes evident, however, when looking at the origin of core concepts of science. In the following, we argue these concepts are not the presupposition of knowledge integration but its results and that integration is never definitive but rather may give way to disintegration. Hence, the core concepts are themselves subject to further transformations, as well as are the disciplines organized around them.

In the core disciplines of the natural sciences as they emerged between the early modern period and the late nineteenth century, a handful of concepts structured a vast array of scientific knowledge. The concepts of space, time, force, motion, matter and a few others played this role for classical Newtonian mechanics; together with the concepts of energy, entropy, field and charge, they also played this role in developed classical physics.[7] The concept of chemical compounds played a similarly foundational role for chemistry (Klein 1994). The concepts of species, gene, selection, variation and adaptation structured classical evolutionary biology,[8] and the concepts of cell, bacterium, pure culture and infection classical microbiology.[9] Second-order concepts, such as 'fact,' 'evidence,' 'proof' and 'objectivity' denote shared control structures and practices aiming at institutionalizing and internalizing the reflective character of scientific thinking, establishing its supposed universality in specific, historically contingent ways.[10]

In retrospect, such core groups of concepts may appear to constitute the starting point for gaining scientific knowledge in their respective fields. A closer historical examination shows, however, that such core groups of concepts usually achieved their privileged position in the organization of knowledge only after a long process of knowledge integration, in a material, social and cognitive sense. The emergence of a core group of foundational concepts in the course of such integration processes can thus be understood as a restructuring of the cognitive

[7] See (Renn 2007a).
[8] See (Beurton et al. 2000; Lefèvre 2009).
[9] See the discussion in (Müller-Wille 2004).
[10] See, for instance (Daston and Galison 2007).

organization of knowledge that was previously acquired under rather contingent circumstances.

Historically, the formulation of the laws of classical physics, for instance, was shaped by the central role of specific challenging objects of early modern technology, such as artillery or the pendulum.[11] They were seen in connection with that other great challenging object of the early modern world, the motion of the planets, leading to Newton's formulation of a concept of force applicable to both. Reflective thinking played an important, but not always appreciated, role in such restructuring processes. This role is evident, for instance, in the attempts by Descartes, Newton and Leibniz to achieve a philosophical integration of physics and mechanics, which largely shaped the emergence of classical physics.[12]

It is particularly evident in historical attempts to provide an explicit philosophical synthesis of scientific knowledge. An outstanding example of the role of reflective thinking in philosophical integrations is the long-lasting influence of Kant's natural philosophy on the self-understanding of classical science.[13] It emerged from the reflective integration of key concepts of early modern science and remained the dominant philosophical background of the increasingly specialized sciences, whatever changes of systems in philosophy took place (Köhnke 1986).

It was a common feature of knowledge integration in the period of classical science, between the early modern period and the late nineteenth century, that foundational, first-order concepts of a particular body of knowledge, such as the concept of force, were exploited to achieve such a philosophical integration. Thus, the mechanistic worldview, dominating physics from the seventeenth to the nineteenth century, could be formulated in terms of matter, motion and force (Dijksterhuis 1983). But the later revolutions of modern science, such as quantum theory or Einstein's theory of relativity, made it evident that such concepts do not correspond to a universal structure of the world or of its understanding by humans.[14] Rather, it became clear that key concepts of classical physics including space, time, matter and force actually correspond to fundamentally anthropomorphic mental models that were no longer adequate when scientific experiences were significantly extended to include such phenomena as the evolution of an expanding universe or the splitting of an atom. From a historical and philosophical perspective, the anthropomorphic origin of some of these concepts had always been more or less discernible (Mach 1989), while it was virtually forgotten in the textbook formulations of the seemingly universal laws of classical physics.

By the nineteenth century a differentiated distribution of labor had been established between different institutions of research and education. Also, institutionalized science policy had emerged as a new form of reflection on the rapid development and increasing significance of science organization. Science began to

[11] See (Renn 2001; Lefèvre et al. 2003).
[12] See, for example, (Damerow et al. 2004; Freudenthal 1986).
[13] See (Friedman 1992; Lefèvre 2000; Zammito 2002).
[14] See (Renn 2007b), in particular (Renn and Sauer 2007).

have a major, global impact on human life. New means of generating energy such as the steam engine, new means of communication such as the telegraph, or new measures against widespread diseases such as antibiotics and vaccination, would have been inconceivable without the close association between science, technology and social and economic development. In addition to the consolidation and specification of the academic disciplines, the era of the Industrial Revolution also saw a further differentiation of modes to produce scientific knowledge, in particular between research more or less closely associated with technological and industrial applications.[15]

Science-based industries, such as the chemical, the electrical and the pharmaceutical industries, came into being, turning the market, alongside the military, into a major driving force of innovation in science as well.[16] As a consequence, the economy of resources and the economy of knowledge became ever more closely intertwined, thus preparing the ground, from the end of the nineteenth century, for the Second Industrial Revolution, associated first with this rise of science-based industries and later with the global spread of electronic appliances.[17] Science thus became part of a self-accelerating process in which science-based technical and commodified applications, such as photography, telecommunication and later computer storage, are being employed as tools for further exploration. The conditions for scaling up the development of science were accordingly themselves a consequence of science and its technological implementation, including the emergence of modern transportation and communication technologies.

Scientific knowledge spread through its increased economic, military and political significance, including the creation of educational institutions with an ever greater penetration of society and extended international collaborations, by way of its technological implementations, including the dissemination of black box instrumentation, but also with imperialism and colonialism. The turn from the nineteenth to the twentieth century was characterized by a growing scientific rivalry triggered by the emergence of Germany and the United States as political-economic powers that challenged British imperialistic hegemony. During this period, the British exported administrative knowledge, practices and institutions as well as Western ideologies such as nationalism; at the same time, local knowledge flowed from colonies to the Western centers. The international regime was based on the theory of free trade and legitimized by it.[18] Because of its association with practical, for instance military, applications, science in this period also began to

[15]See (Damerow and Lefèvre 1998; Carrier 2008; Klein 2012).
[16]See (Baracca et al. 1979; Hughes 1983). For the chemical industry, see the classic study (Haber 1958). For a more recent approach, see (Aftalion 1991). For the pharmaceutical industry, see (Friedrich and Müller-Jahncke 2005).
[17]See the definitions given by Carlo Schmid (1956) and Joel Mokyr (1998). Schmid defines the economic changes after World War II as the Second Industrial Revolution, while according to Mokyr, it occurred between the last third of the nineteenth century and the beginning of World War I.
[18]See (Gallagher and Robindon 1953; Semmel 1970).

serve as an incentive for cultural assimilation and for the creation of social systems capable of absorbing it. Vice versa, new disciplines such as ethnology and anthropology emerged, integrating knowledge acquired during colonization into the system of science.[19]

24.3 The Disintegration of Knowledge and the Globalization of Science in the Age of the Great Wars

During the First World War, science became a major military and economic factor, enhancing the tension between its international character and its involvement in national policies.[20] The interwar period between 1918 and 1939 was characterized, on the one hand, by the disintegration of international cooperation within the West and the emergence of nationalistic policies emphasizing isolationism and economic autarchy and, on the other hand, by attempts to create new international organizations such as the League of Nations, the Red Cross and the Socialist International. At the same time, this period was a transition from British to US economic and political dominance, and from the international regime of free trade to that of an "embedded liberalism," which included protectionist elements. Nationalistic tendencies in terms of economic regime affected the flow of knowledge and the possibilities of scientific cooperation, both among Western countries and between them and peripheral and semi-peripheral countries.

The foundational concepts which had emerged from the first ground-breaking periods of knowledge integration, such as those of space, time, matter and force in the case of classical physics, proved to be extremely stable in the face of an enormous growth of knowledge in the course of the further development of science. In fact, they even were considered to have a priori status, not subject to any changes by the accumulation of knowledge. Nevertheless, core scientific disciplines witnessed fundamental changes of precisely this core group of foundational concepts in the period between the mid-nineteenth and the mid-twentieth century. These fundamental changes were preceded by more or less extended periods of knowledge disintegration, in which the established cognitive organization of knowledge became problematic. Paradoxically, it appears that the essential mechanisms at work in these periods of destabilization were of the same nature as those which functioned in the original processes of knowledge integration.

When classical physics reached a crisis at the turn from the nineteenth to the twentieth century, Kantianism saw a spectacular revival, not only in the modified form of Neo-Kantianism and conventionalism, but also in the emergence of a new type of philosophical integration, often labeled as "scientific philosophy." It was a last attempt to achieve an overarching scientific worldview with the help of

[19] See (Harris 1968; Asad 1973; Kuklick 1991). The close relationship between colonialism and the emerging field of anthropology (ethnology) is also discernable during the eighteenth century. For the emergence of ethnography during the exploration and colonization of eighteenth-century Russia, see (Vermeulen 2008, 2012).
[20] See (Ash 1996; Berg et al. 2009).

philosophical methods that entered into the semantics of scientific concepts. This attempt failed, however, for a number of reasons, both intrinsic and extrinsic, and gave way to the so-called "linguistic" turn of philosophy.[21] The novel feature of philosophical integrations after the linguistic turn was that they were based on a reflection on the syntactic structures of the representation of scientific knowledge by language. As a consequence, the basic concepts of this integration no longer had any direct relation to first-order concepts, so that the integration became content-independent and formal.

Since the beginning of the twentieth century, reflection on science tends to be separated into four branches: a philosophical-normative branch, a historical-descriptive branch, a political-pragmatic branch and the reflection taking place within science itself. The result was a split of rationality, largely separating science from a reflection referring to its contents as well as to its contexts and its societal conditions.[22] However, such a separation could obviously not be absolute and was challenged by alternative interpretations of science as well as by often ideologically motivated attempts at its alternative systematization and organization.[23]

The very possibility of scientific progress continued, in any case, to depend on processes of knowledge integration and disintegration mediated by reflection. Such processes of integration and disintegration within and between disciplines always remained closely connected with first-order concepts and their reflection in view of the acquisition of new knowledge. An outstanding example is the disintegration of classical physics around the turn of the century and the subsequent partial reintegration into global theories such as relativity and quantum physics, emerging as a consequence of probing deeper into the microstructure of matter and of exploring the physical constitution of the universe, but also in the sequel of new technical developments. The emergence of these theories can be understood as resulting from a reflective reorganization of existing and newly acquired knowledge triggered by borderline problems within the wider field of physics, mathematics, astronomy and chemistry.

The disciplinary specialization of science in the nineteenth century had generated these borderline problems located at the intersection of knowledge systems organized into different disciplines or subdisciplines (Renn 2007a). Through these borderline problems, distinct conceptual frameworks came into contact and sometimes into conflict with each other, triggering their integration and reorganization. Quantum physics, for example, emerged at the beginning of the twentieth century because the new technology of electric illumination and its widespread implementation required measures of control and standardization on the part of state-supported research institutions. These measures triggered research on a bor-

[21] See, for example, (Carnap 1934; Wittgenstein 1961; Hintikka and Hintikka 1986; Awoday and Carus 2007). For further discussion, see (Engler and Renn 2012).
[22] For a global history of rationality in which the split of rationality from other human faculties plays a central role, see (Vietta 2012).
[23] For alternative interpretations, see (Rheinberger 1997; Freudenthal and McLaughlin 2009). For Soviet Marxism as an example of an alternative systematization, see (Graham 1993).

derline problem between electromagnetism and heat theory, the so-called black body problem, which in turn gave rise to questioning the fundamental concepts of classical physics. New concepts, such as the quantization of energy, were formulated in response to this crisis. These concepts turned out to be relevant for a wider domain of physics and chemistry as well, expanding the range of the crisis and eventually leading to a completely new understanding of the microscopic structure of matter and radiation (Büttner et al. 2003).

Such processes of reconceptualization typically involved rearrangements on all levels, institutional as well as cognitive, including the refocusing of traditional research activities induced by the discovery of a new common thread, connecting hitherto separate problems. Also typical was the interaction of heuristic programs, which aim at knowledge integration, and traditional structures of knowledge, be they cognitive or social, which are disintegrating. The heuristic programs were comparable to the philosophical programs of an earlier period (mentioned above), although they were now usually formulated from an inner-scientific perspective (which, of course, does not exclude influences from philosophy), and could even take the form of science policy directed at regulating integration and disintegration process of knowledge by institutional organization. Due to the recursive blindness of the sciences and the split of rationality, the intellectual resources offered by prior historical experiences remained, however, often untapped.

Science in the twentieth century was characterized by an acceleration of scientific activity, by increasing specialization and professionalization, as well as by an ensuing fragmentation of knowledge, by a growing commercialization and militarization of knowledge and by the emergence of Big Science.[24] Big Science is the pursuit of science on an industrial scale, with massive investments in equipment and personnel, with an elaborate distribution of labor, and governed by management processes that may involve strong political, economic and military interests. While the emergence of quantum physics in the first quarter of the twentieth century still happened in a rather haphazard fashion that may be described as "big science in an unorganized way," Big Science in the proper sense emerged in the context of the Manhattan Project to produce the atomic bomb during World War II.[25]

More generally, during World War II, science was massively taken into the service of military, economic and political operations, including for singular crimes against humanity as the Holocaust.[26] This happened, however not exclusively and perhaps not even predominantly in terms of the top-down mobilization of its resources by states, but rather by a self-mobilization of science in response to new funding and career opportunities. On the whole, science turned out to

[24]For diverse perspectives on this issue, see (Price 1963; Weber 1965; Husserl and Ströker 1977; Forman 1987; Carrier 2008).

[25]See (Herken 1980; Rhodes 1986; Hughes 2002; Kelly 2007). See also (Garwin and Charpak 2002) and chapter 27 in this volume.

[26]See (Walker 1989; Trischler 2000, 2001; Maier 2002; Weindling 2004; Schmaltz 2005; Maier 2007).

be incapable of coping with the ethical challenges posed by the transformation of its scaled-up economic, political and military implications into criminal abuse. The increased involvement of science in societal issues was, due to the split of its reflexivity into contemplative and pragmatic branches, not balanced by an institutional and intellectual self-organization and self-awareness of science that could have strengthened its autonomy and acted as a counterforce against its instrumentalization.

The period after World War II up to the 1970s was characterized by a combination of international cooperation and world governance on the one hand, and strong statehood on the other. The international regime was such that it allowed for flexibility in the ways states and governments could respond to local challenges without breaching what was conceived legitimate state action. The Cold War, of course, was a decisive factor that shaped the global arena as well as the possible forms of statehood. This international arrangement brought about new modes of knowledge production at national and international levels. The model of Big Science also spread into the non-military domain, while the strong ties between science and the military created during World War II were reinforced in the context of the Cold War.[27]

The launch of the first artificial satellite "Sputnik 1" by the Soviet Union in 1957 led to massive investments into science and education by the Western nations to catch up with the technological advance represented by this achievement. In the United States, federal research and development budget and government funds for universities increased substantially. With the set-up of the President's Science Advisory Committee and the Presidential Science Advisor, focusing on the space program and on strategic weapons, scientists moved closer to government (Geiger 1997). Military research and the space program generated spin-off technologies, such as the microchip, and new materials. Political boundary conditions and the market imposed strong external constraints on the self-organization of science, also acting as a selective force on its intellectual development.[28]

Yet the network of scientific knowledge continued to unfold its own, unpredictable dynamics, which can never be completely controlled by external forces. Even in the presence of strong outside influences, the development of science remains a largely self-organizing process—not least because of its global character—that may or may not be optimized by a society for its own purposes. It is this process that, at the same time, exposes a society to a feedback loop of reflection about itself, making it necessary to confront some of its basic tenets, for instance about economy, justice, health or environment, with the cognitive potentials inherent in science.

[27] See (Galison and Hevly 1992; Trischler 2000; Krige 2006a).

[28] For detailed studies of the corresponding German situation, see (Trischler and vom Bruch 1999; Ritter et al. 1999; Trischler 2002).

24.4 Modes of Reflection on Globalized Science in the Age of Liberalization

The great pitfalls of science in the twentieth century had made it abundantly clear that scientific innovation is not just an internal matter of science and its irresistible progress. By the 1970s, it had become evident that the very concept of innovation, being an image of knowledge, involves ideas about what science means and where it is leading. These ideas turned out to be as profoundly shaped by science itself as by the world outside science. It had also become apparent that considering innovation without reflecting on its nature as an image of science effectively renounces the freedom to consciously set priorities. The increasingly incisive consequences of scientific progress suggested to take such reflections into account in determining what innovation actually is and what it should be.[29]

The period after the 1970s was characterized by a number of factors. These include the following: the disintegration of the Bretton Woods agreements and the shift to "floating" exchange rates, a "liberalization" of capital and good flows, the emergence of new forms of transnational and domestic governance (the "New Public Management" movement), the emergence of new information technologies, the dissolution of the communist block, the emergence of Asian economies, but also by an increased awareness of the limitations of global natural resources and by the above-mentioned skepticism with regard to scientific progress understood as a self-evident component of modern industrial societies.[30]

It had become clear, in particular, that political, economic or military decisions, but also the market and public opinion, could affect the pathway of scientific developments with long-term consequences. Also, the continued existence of traditional societies still living in the pre-industrial age suggested that the development of human societies is not necessarily linked to an accelerating development of technology, and not at all with the emergence and cultivation of science. Obviously, science was only one of many possible forms of expressing human culture, a realization that suggested approaches to science studies which no longer accept unidirectional concepts of modernity and even doubt the role of science as a privileged form of knowledge.[31]

On a political level, the development of science in democratic societies is exposed to a feedback loop in which it is confronted with the expectations, anxieties and constraints of public opinion. Public and private funding of science in democratic societies requires justification for the investments that may affect the direction of the development or even impose severe limitations on it. At the borderlines between science and society, public images of science are generated,

[29] See (Habermas 1968; Kuhn 1970; Elkana 1974; Feyerabend 1975, 1976). See also the history of the foundation of the Max Planck Institute for the Study of Societies in Starnberg, Germany, in 1970 by Carl Friedrich von Weizsäcker, as discussed in (Leendertz 2010).

[30] For the following, see (Renn et al. 2002; Renn 2003).

[31] See (Latour and Woolgar 1979; Latour 1992; Knorr-Cetina 1981, 1999; Shapin and Schaffer 1985; Shapin 1996).

often amalgamated with religious or ideological components that modulate their interaction. For the non-expert public, it has often been difficult to distinguish between science and pseudoscience, as the spread of creationism, fundamentalist ideas about Islamic science, or Scientology illustrate. As a consequence, the way a particular society can make use of scientific knowledge may be severely restricted. The public accessibility of scientific knowledge and the active participation of science in public dialogue have thus become a major challenge for societies relying on the advancement of science, that is, in the long run, for all human societies.

With the Bayh Dole Act from 1980, for instance, a uniform patent policy was introduced in the US that enables universities and non-profit organizations to register patents for inventions made in federally funded research projects. The intention was to encourage universities to more strongly engage in technology transfer and to increase commercialization, thus strenghtening US economic competiveness. While this policy has led to the creation of thousands of spin-off companies contributing billions of dollars to the American economy, it has also tended to limit perspectives to short-term profits rather than minding the benefits of society at large.

National science policies are increasingly oriented toward international competitiveness. No major society today can permit itself not to foster and regulate science and education systems according to globalized models of schools and universities. Asian universities, for instance, have a strong orientation towards international (American-biased) rankings, such as the Shanghai ranking and the Times Higher Education World University Rankings, and adjust their policies accordingly. The Brain 21 initiative in Korea aims at bringing the ten best Korean universities within the top 100 of the world and to join the world's top ten nations in high-level publications.

Competition is affecting science in the form of the demand to cope with economic globalization, as illustrated by Europe's Lisbon strategy aiming at Europe becoming "the most competitive and dynamic, knowledge-based economy in the world …." In addition, competition takes on the form of a governance mode increasingly used in science management.[32] Incentives are being introduced both on the individual level, for instance by incentive-based management of research by contractually specified objectives, and on the institutional level, for instance by implementing quasi-markets through an increasing competition for third-party-funding and through changing from long-term institutional financial support to short- and mid-term program-oriented financial support.

This encouragement of international competitiveness strengthens globalized models of science and education even more, in particular as they still harbor much of the lore of the Western Enlightenment. But the ensuing globalization of knowledge tends to replace reflection with competitiveness and to downplay the role of specific contexts and local knowledge in favor of supposedly universalist principles of science. Yet it is through this perspective that most societies have

[32] For a discussion of models of science governance, see (Stensaker et al. 2006).

come to view their problems, often disregarding the potential inherent in their own particular traditions or else in the opportunities for changing those principles, opportunities that sometimes only come with a decoupling from global trends and adapting science policy to local conditions.[33]

Science has become, in any case, a medium through which societies of a globalized world reflect upon themselves, albeit often in an indirect or haphazard and sometimes even fatal way. Much of the inner workings of present societies, their economies, their political systems, their cultural traditions and mindsets, and even their mechanisms of biological reproduction, have themselves become the object of science, sometimes with immediate self-regulatory consequences. However, often the most relevant knowledge for a society's future is not generated by its academic institutions, for instance regarding fundamental economic decisions or health care; and if it is available, it is not being implemented because of the incapability of the political system to absorb this knowledge. Nevertheless, scientific knowledge has become an almost unavoidable component of any intellectual attempt to come to terms with human society on a global scale. This becomes particularly evident in attempts to ban, use or even modify science for ideological purposes, as were undertaken under the Nazi regime in Germany or in Soviet Russia. While it has been possible to abuse science for crimes against humanity, it has not been possible to simply abandon science or substitute it with an alternative. The role of scientific knowledge for a society's self-reflection is also clear from the inflation of scientific expertise on issues such as global warming, nuclear policy, energy policy, and national economic policies where conflicting positions are legitimized by expertise and counterexpertise.[34]

Looking back at past images of science, implying expectations for future innovations, their dependence on both cultural values and the limited knowledge available in a given historical situation becomes immediately evident, as it is the case, with the great visions of the end of science, recurrent in history to this day (Horgan 1996). In hindsight, they all appear just as naive as predictions about future technological developments, such as the claim of a popular science magazine in 1949 that, in the future, computers would weigh less than 1.5 tons (Hamilton 1949, 258). But while real innovations often emerge when and where they are least expected, expectations nevertheless have a profound impact on the conditions for innovation. This is because images of science embodying these expectations determine strategies for knowledge acquisition and with them the organizational and institutional structure of science.

Scientific innovation results from a co-evolution of scientific knowledge, images of science, and strategies for knowledge acquisition governed by these images; in short, it depends on the dominant epistemic constellation (see chapter 1). In the current era, the increasingly rapid accumulation of scientific knowledge and the

[33]See chapters 16 and 25. See also (Baracca and Renn forthcoming). The following is based on (Renn et al. 2002).

[34]See, for example, (Oreskes 2010).

growing resources involved in producing it therefore make it necessary to also constantly adjust the strategies for knowledge acquisition and to reexamine images of science that may long have been superseded by this accelerating development. The co-evolution of scientific knowledge, images of science, and strategies for knowledge acquisition is a complex process that has hardly been understood, also because the history of scientific knowledge and the sociology of scientific institutions have been traditionally studied separate from each other.

24.5 The Persistence of the "Classical Image of Science"

For most practical concerns, structures of basic research are still mostly conceived in terms of what one may call the "classical image of science." It has, in fact, become so self-evident that it is hardly conceivable that science could have ever worked without being guided by the distinctions, criteria, and values it imposes. According to the classical image of science, it seems natural, for instance, that one has to distinguish between basic and applied science, that both education and research are organized in terms of disciplines, that great breakthroughs are usually the accomplishments of a few outstanding individuals who publish their discoveries in the most prestigious journals of their fields after the quality of their work has been assessed by their peers. Disciplinary structures which guarantee a competent distribution of labor in science, the identification of innovation with the achievements of individuals, the role of journals and peer review as quality filters—these are all elements of a coherent system of the production and dissemination of scientific knowledge that has indeed worked fairly well in the past.

At present, the system is challenged by several developments that are becoming increasingly dramatic. There is, first of all, the problem of size, both of science itself (in terms of manpower, resources, organization and industrial application) and of the quantity of publications it generates. The tremendous growth of science has been too large for commercial publishers to cope with, forcing certain fields into self-organizing open-access online publication initiatives.[35] The natural and most wide-spread response to this challenge of size is, however, to strengthen the values underlying the classical system of science with the help of an increasingly extended institutional scaffolding, built with the purpose of reinforcing these values by imposing externally controllable criteria. But this externalization of scientific standards has, at the same time, the unavoidable effect of weakening the underlying values by curtailing the significance of the intellectual exchange of the scientific community in favor of mechanisms of social control, replacing, for instance, personal judgements by formal evaluations, reading by counting, quality by quantity. While these mechanisms for steering science still draw their legitimacy from the classical image of science, they have actually produced their own secondary values—always with the danger of degenerating into fetishes such as

[35]See chapter 28.

the impact factor—which encourage the production of more and more publications representing ever-smaller units with the risk of eventually drowning science in an ocean of information, that is, potential knowledge, without assessing its relevance to society at large.[36]

Another dimension of the classical image of science that has become problematic is the assumption that science policy can be sure of its standards of judgement without subjecting them time and again to an evaluation of their adequacy to actual research processes and their real-world contexts. According to the classical image of science, if an evaluation is necessary it is that of science by science organization and not vice versa. Evaluation, like other forms of reflection on science, such as methodology, is a pursuit that to a great extent can supposedly be decoupled from the contents of science; scientific research and science organization belong accordingly to different epistemic spheres, just like content and form, with the latter being largely independent of the former.

However, it has meanwhile become a widespread experience that the interdisciplinary nature of most worthwhile scientific problems makes it necessary to employ resources for tackling them which are usually not readily available as part of the established institutional framework of science or that such problems require reflections on social, cultural and ethical contexts, traditionally reserved to the sphere of applied science. Successfully mastering problems of basic science hence often includes wrestling with issues of science policy. In any case, it may turn out to be a vital problem for basic research if the growing dominance of external criteria of validation, associated with an increasing pressure to legitimize the public resources spent on science, risks obscuring the perception of real problems. Is it indeed always safe to assume that a scientific enterprise which is highly effective if measured by a cost-benefit analysis, holding, for instance, the quantity of publications against the investment of funds, is also actually successful in coping with key human issues, be they questions of survival or simply the quest for knowledge? How can we be sure that the structures of specialized science and of science under the pressure of also quickly rendering economically tangible results do not blind us precisely against those potentials that may offer unexpected pathways to urgently required new solutions?

One of the most salient features of the present historical moment is that the institutional structures of science are permanently challenged by the research process they are supposed to channel, just as most major projects of basic research are permanently forced to reinvent the conditions for their realizability. In addition, they should also be able to reflect their economic, societal and moral contexts, as well as their relationships with other research endeavors. This contrasts with the more or less clear separation of levels of reflection within the classical image of science according to which organizational issues are to a great extent left to administrators, politicians or scientists no longer concerned with research, and where the fixed intellectual framework of a discipline can guarantee that independently

[36] See (Max-Planck-Forum 2003).

achieved results are automatically embedded in the larger whole—even if single specialists are no longer capable of connecting them in their own minds. In short, today's scientists are living in an age that demands participation on all levels of the scientific campaign. This includes its strategic issues, rather than just fulfilling a duty as a private on the battlefield of a specialized discipline, which was all that seemed necessary in the past era of classical science.

After the great pitfalls of science in the twentieth century, from the production of poison gas via the involvement of science in the Holocaust to the development of nuclear weapons, this historical lesson has mostly taken the form of moral appeals to the responsibility of the individual scientists for the application of their insights. At the same time, however, the growing industrialization of science made it increasingly difficult to actually cope with such individual responsibility. As it seems, the twenty-first century now transposes the issue of responsibility in part back into the inner workings of science. When dealing with modern biology, for instance, intellectual issues such as problem definition, institutional and economical issues such as the alternative between open source policy and intellectual capitalism, and moral issues such as the use of stem cells can no longer be adequately divided into small morsels with the idea of assigning separate responsibilities for each of them to biologists, politicians, and philosophers respectively, who then have only to join their specialistic competencies—and, of course, the interests of their lobbies—when meeting in advisory boards or addressing the public.

The interlocking of cognitive, social, cultural and moral dimensions in intricate situations that is becoming the hallmark of science in the twenty-first century is no doubt an additional challenge of complexity but also an opportunity for science to regain intellectual and moral autonomy.[37] Clearly this opportunity can only be used if the freedom of self-organization of science, which is at the roots of its innovative potential, is strengthened rather than weakened by further layers of hierarchical control; if problem choice can be accompanied by reflection instead of being enforced by formalized career patterns; if the necessary reality checks of intellectual ventures are not taken as a pretext for a confinement of science to economically profitable applications; if the social and institutional structures of science encourage intellectual mobility and recruitment from all strata and all parts of a global society rather than the defense of local prebends; and if the new ways of access to scientific information are not blocked by its transformation into a commodity.

This necessity, however, is in conflict with the internal pressure generated by the competition within the worldwide academic system to produce more and ever more specialized results, in general inaccessible not only to a wider public, but also to scientists from other disciplines. The growth of science, as mentioned above, has enhanced tendencies to standardize, institutionalize and automatize many of the control procedures which, at the beginning of modern science, were merely

[37]For studies of knowledge generation based on model systems, cases and exemplary narratives, see (Wise 2004; Creager et al. 2007).

an expression of more or less informal reflections about the quality of scientific achievements within the community of peers. This institutionalization of scientific standards has ensured a high level of professionality and quality control of the scientific production, in spite of its enormous growth and its worldwide spread. To some extent, it has even helped to maintain compatibility and complementarity among scientific results produced in widely distinct branches of academia. But forcing scientific information into small contributions, together with the formalization of quality control and hence of an important aspect of reflection on the meaning of scientific results, has also contributed to the fragmentation and disintegration of science, as well as to the exclusion of important insights attainable only far from the mainstream, not to mention the lost opportunities to tackle grand challenges transcending any disciplinary borders.

24.6 The Formation of Socioepistemic Complexes and the Onset of Socioepistemic Evolution

The globalization of knowledge today is a consequence of two processes: the intrinsic globalization of science and the fundamental role that knowledge, particularly scientific knowledge, has assumed in other, economic, political and cultural globalization processes. As for the first process, we have seen that the globalization of science has become a self-organizing, global distribution of intellectual labor, reshaping national institutional structures and local epistemic traditions. At least in the natural sciences, a global epistemic community has emerged with common standards, concepts and methods. Yet, as we also stressed in previous chapters, globalized science results from a synthesis of many local traditions and not from a single dominant Western model, and these local contexts continue to play a non-negligible role. The process in which globalized science emerged is deeply historical and dependent on contingent contexts and chance constellations, which, in the course of history, are transformed into necessary preconditions for further development.

As for the second, extrinsic process concerning the role of knowledge in other globalization processes—whether political, economic or cultural—it is evidently the case that any flow of scientific knowledge that comes to be associated with the international policy of individual states or with multinational actors, such as NATO, IBM, UNESCO, Al-Qaeda (e.g., by funding or espionage), unavoidably takes on a global character.

A critical link between intrinsic and extrinsic aspects of the globalization of scientific knowledge is found in the media and types of communication in science, which are the currency of an epistemic economy. Another critical link is the mechanisms of effective knowledge transmission between science, policy and society. Effective knowledge transmission means not just making knowledge available to different target groups, but at the same time creating conditions for implementing knowledge in practical contexts. As we showed in chapter 16, when transmitted to a different sociocultural environment, supposedly global knowledge, such as knowledge about central banking, may acquire a different meaning and be used for different purposes.

One important result of the interaction between intrinsic and extrinsic processes of the globalization of knowledge in the long twentieth century, that is in the period between ca. 1870 and today, is the emergence of global objects of science, in particular global human challenges such as climate change, scarcity of water, global food provision, reliable energy supply, sustainable demographic development and nuclear proliferation.[38] Dealing with these global themes, scientific fields including meteorology, seismology, oceanography, environmental science, epidemiology, earth system sciences, astronomy, space-bound science but also sociology, political science and economics necessarily operate on a global scale.

The mitigation and handling of global challenges to humanity are inherently connected, both to the development of policies and to the production of scientific knowledge on a global scale. Here, policies do not just shape the organizational form of science and determine research priorities—while there is, for example, an Intergovernmental Panel on Climate Change (IPCC) dealing with climate change, no comparable organization exists for dealing with the challenges of energy supply. Scientific knowledge also crucially shapes policies and politics. But it is as yet unclear which international arrangements are most effective to encounter collective international problems, which arrangements actually bring about scientific advancement, how international coordination enables the establishment of specific international research projects, whether global coordination is under all circumstances favorable to the advancement science, when globalized science serves as an ideological tool for legitimizing collective political actions and when it actually becomes a resource structuring international regimes, shaping global images of knowledge or enabling new forms of global governance.

It is evident that no simplistic rationalistic-technocratic model of policy-making according to the scheme of "speaking truth to power" adequately describes the current situation. It is generally not the case that science first identifies a problem then offers a solution that politics finally has to implement. Such a procedure does not reflect the actual dynamics of coping with these challenges. Neither is "truth" produced in an area free of interests, values and uncertainties, nor is "power" simply adopting and implementing knowledge free of normative considerations.[39] Some approaches therefore see "epistemic communities" in a decisive role for triggering processes of learning in policy-making and beyond.[40]

More specifically, socioepistemic complexes have formed that involve such communities in the production of scientific knowledge in large-scale technological ventures, in global infrastructures and regulations, or in worldwide operating

[38] For the example of global food provision, see (Nützenadel and Trentmann 2008); for the problem of water supply, see (UNESCO 2009); for other challenges, see the remainder of this book.
[39] See (Oreskes 2010).
[40] See, for example, (Haas 1992). See also (Silberglitt et al. 2006; Ozolina et al. 2009; Rockström 2009).

enterprises. They may still largely depend on traditional sociocultural modes of knowledge generation, but they may also create new modes, such as that embodied in the collective production of open source software. These socioepistemic complexes cause changes on a global scale that cannot be easily undone. Examples are the global networks of nuclear technology, of mobility, or of information and communication. Governance of such socioepistemic complexes requires the production of more and more scientific knowledge. They even endanger their ecological and social substrata unless new scientific knowledge continually becomes available. As a consequence, they sharpen the dilemma of human freedom, increasing humanity's potential to act but making the world increasingly dependent on the appropriate use of this potential.

It is thus a further consequence of the interaction between intrinsic and extrinsic processes of the globalization of scientific knowledge that sociocultural evolution in general, including economic and political globalization, becomes more dependent, both on the production of scientific knowledge and on the possibility of coping with the global challenges for humanity mentioned above. This growing dependence, mediated by global socioepistemic complexes, may be characterized as a new stage in human development, as a socioepistemic evolution.[41] We speak here of evolution in the general sense of a developmental process that is not determined by its starting point, but that constantly transforms contingent circumstances into unchangeable prerequisites for further development so that the process acquires memory. The contingent circumstances come from the environment of the process, but they may also be generated by the process itself so that the development becomes indeterministic and its outcome unpredictable.

As a consequence, such an evolutionary developmental process is an interactive learning process of a very general kind in which extrinsic features of the environment are internalized, at the same time, the environment itself is transformed by the developmental process, accounting for its self-referential character. The interaction between a developmental process and its environment can take different forms. In biological evolution, the generalized learning process takes the form of variation and natural selection. In sociocultural evolution, it takes the form of human interaction with nature by means of material artifacts, associated with the accumulation of knowledge shared within a given society. In socioepistemic evolution, it takes the form of humanity's interaction with its planetary environment by means of a globally effective material culture (determining a developmental stage characterized as anthropocene), associated with the accumulation of globalized scientific knowledge.

Socioepistemic evolution is the process in which the global production of more and increasingly diversified scientific knowledge about humanity's interaction with nature becomes critical for its survival. In the Paleolithic age, sociocultural evolution took over from biological evolution in such a way that the human species has become dependent on it. Meanwhile, the generation and transmission of scientific

[41] See the discussion in chapter 1.

knowledge has similarly become quintessential for human survival. The demand to produce the appropriate scientific knowledge may exceed the potential of traditional modes of the generation of knowledge in sociocultural evolution, such as state-supported basic research or market-driven applied research, and necessitate new forms of knowledge production. Some of these new forms of knowledge production are emerging in connection with the socioepistemic complexes marking the transition from sociocultural to epistemic evolution, such as the global knowledge production associated with the World Wide Web. But just as there were—and are—many pathways of sociocultural evolution (from clans, feudal systems, state bureaucracies to market economies—with or without democracy), there are and also will be a variety of pathways into socioepistemic evolution, paradigmatically represented by some of the developments discussed in the following.

24.7 The Perspectives of Social Studies of Science and of Historical Epistemology

The recent changes in higher education and research associated with globalization processes are also the subject of theoretical approaches from the social studies of science. While it is argued that we are facing a dramatic change of science as a social and cognitive system, comparable to the transformation accompanying the Industrial Revolution, the long-term historical origin of these changes tends to be neglected and the dichotomy between "old" and "new" science is overemphasized.[42]

Also, the transformation of the academic world is conceived not so much in terms of a globalization of knowledge with its own dynamics, but rather as a consequence of economic globalization, for instance, as a reaction to rising societal demands to gain revenues from publicly funded science in an increasingly competitive world. The "new" science is characterized as "mode 2" (Gibbons et al. 1994; Nowotny et al. 2001), as "post-academic science" (Ziman 2000), as "post-normal science" (Funtowicz and Ravetz 1993), as "academic capitalism" (Slaughter and Leslie 1997) or in the context of the "triple helix" model of university-government-industry relations (Etzkowitz and Leydesdorff 1997).

For our discussion here, however, it is less relevant whether a clear separation of the spheres of academia and society has ever existed in the past (mode 1 science), or whether knowledge in the future will really be produced by interdisciplinary task forces addressing problems of social and economic importance, such that scientific disciplines will vanish (mode 2 science). What characterizes epistemic evolution is the transformation of the production of scientific knowledge from a contingency of sociocultural evolution into a necessary condition for human survival, whatever specific form of science is involved and whatever mode of knowledge production may ultimately turn out to be suited to ensure that survival.

Without more detailed studies taking into account not only sociological but also epistemological and historical dimensions of the global development of science

[42] See, for example, the critique in (Weingart 1997; Pestre 2000; Shinn 2002).

and technology, overall trends will be difficult to assess. The development and diffusion of knowledge in modern science is, in any case, not just subject to unidirectional tendencies of growth, expansion, specialization and commodification, although the commercialization of science has reached a new quality and intensity being intertwined with a globalized market. There are even strong tendencies in the opposite direction, for instance the growing recognition of the importance of open access, knowledge sharing and collaboration not impeded by a narrow interpretation of intellectual property rights. Also, the standard picture of an ever expanding science ignores the fact that even where scaling-up processes prevail, they may actually be due to quite diverse developmental processes of the different branches of science in interaction with its environment.

Clearly, the ever increasing differentiation of science is counterbalanced by overarching knowledge integration and unification processes as in the convergence, at least with regard to certain problems, of physics and chemistry, and chemistry and biology. However, the potential of such unifications as a countervailing force to knowledge fragmentation has typically met with a number of extrinsic obstacles, in particular linguistic, cultural, economic, juridical as well as political and ideological constraints. At the same time, there have been intrinsic obstacles, such as the gap between theory and data existing in such fields as economics, the neurosciences, psychology and surface physics.

More generally, it has turned out to be difficult, given the past success of seemingly universalist principles in science and their implementations, to take into account the possibility that different contexts may necessitate different ways of conceptualizing and implementing scientific knowledge. Reflecting on these contexts is also difficult because knowledge is embodied in different forms of representation: in institutions, individuals, instruments, texts and images. These various vehicles are subject to different interfaces between science and its environment and have different implications for the mobility or "liquidity" of the knowledge they carry. As we have emphasized above, each field of science may have its own characteristic trajectory of recursive blindness that may also affect the potential for its integration into other fields.

In psychology, for instance, we often still witness a rather artificial separation between studies focused on the individual under more or less universalist perspectives, from studies of the social, cultural and psychological context of individuals and collectives. Similarly, in economic studies, the role of distinct historical pathways and cultural settings still tends to be neglected in favor of simplified assumptions about a more or less bounded rationality.[43] The humanities are just beginning to avail themselves of the possibilities to overcome traditional disciplinary boundaries in favor of integrated accounts bringing together their sophisticated reflective traditions with the wealth of data that is now becoming available and, due to the progess of information technologies, manageable. Physics was in the past characterized by successful integration processes resulting in seemingly universal

[43]See the discussion in (Kahneman 2011).

principles and foundational concepts. In the future, these integration processes may depend also on a more explicit reflection on its proliferation into diverse subfields, the concrete contexts of its multifaceted applications, and their repercussions of these processes on the conceptual organization and unity of physics.[44]

The globalization of modern science involves various types of knowledge. In addition to the classification outlined in the general introduction (chapter 1), one may distinguish between knowledge systems related to the classical disciplines, knowledge systems related to socioepistemic complexes, and second-order knowledge embodied in science policy and organization. One may also distinguish “truth-oriented knowledge” from “technology-oriented knowledge” on the basis of its ethos of autonomy in relation to political institutions and market demands. It is manifested not so much in the actual autonomy of knowledge but rather in the tendency of knowledge producers to demand such autonomy and to legitimize it. “Policy-relevant knowledge” has direct implications for policy making and governance. Policy relevant knowledge is built on truth- and technology-oriented knowledge. For example, nuclear physics started as truth-oriented knowledge, and later on assumed technological and policy implications. The passage from one type of knowledge to another evidently also affects the modes of production and distribution of knowledge. Each of these types of knowledge is likely to be distributed by a different transfer mechanism: truth-oriented knowledge by epistemic networks, technology-oriented knowledge by market mechanisms and policy-oriented knowledge by hierarchical mechanisms.

Scientific knowledge itself comprises several layers: familiarity with elaborate theoretical frameworks, largely documented in texts, with methodologies, often only implicit in scientific practice, and technological knowledge about handling relevant equipment. Scientific knowledge is furthermore accompanied by meta-knowledge about the meaning and goals of science, its role in society, its relation to other pursuits, its organization, and so forth. Scientific practice would, however, be impossible without also involving intuitive and practical knowledge of the most diverse kinds, from social competence via manual dexterity to language skills or the ability to handle complex symbol systems. Since scientific practice does not take place in isolation but is embedded in specific cultural, social and technological environments, one also has to pay attention to the knowledge related to these environments and the ways in which it intersects with scientific knowledge proper. If we consider science in action, all of these types of knowledge play a role.

The globalization of modern science affects them in different ways. Different fields of science rely, for instance, in different ways on language skills: in general the humanities depend on it more than do the natural sciences. Consequently, the spread of scientific knowledge may become affected by the worldwide distribution of linguistic competence in the lingua franca of a given field. Since science has a different status in different societies, the transfer of scientific knowledge inevitably involves a transformation of meta-knowledge with possible repercussions on the

[44] See the discussion in (Galison and Stump 1996).

body of knowledge as well. But scientific knowledge transferred to another context may also be confronted with different technological environments, leading to new insights or hindering the reproduction of ones already achieved in new locations.

It may thus appear that the transfer of scientific knowledge to diverse environments almost unavoidably leads to a splintering, which may even risk endangering its coherence, in a way similar to the splitting of a language as a consequence of the spreading and separation of its speakers.[45] But similar to the case of a language which is preserved intact during such a process, in science it is the continued exchange and equilibration processes among the community of its practitioners that make sure that globalization works in general toward a differentiation and enrichment rather than toward speciation. In addition, one has to realize that it is rarely single components of scientific knowledge that are being transferred, but almost always systems of knowledge. As a consequence, scientific knowledge displays a self-organizing capacity in transfer processes, making it possible to reconstruct it even from fragments if necessary. Yet because what is thus reconstructed is not necessarily a true copy of the original, this self-organizing capacity becomes another source of the diversification of scientific knowledge in globalization processes (see chapter 9).

24.8 Pathways to Socioepistemic Evolution

In the chapters that follow, different pathways of the development of globalized science are analyzed, representing different constellations of knowledge, economic structures, societal regulations and policies, as well as challenges to human survival. Thus, the politically regulated dissemination of Big Science-based technology of a dual-use character is compared to the bottom-up global distribution of labor in Big Science without such dual-use implications.[46] In addition, different models and motivations for the globalization of science are examined. While local hubs of science have attracted international researchers in the development of molecular biology, the Conseil Européen pour la Recherche Nucléaire (CERN) was set up with the explicit purpose of facilitating the maximum possible international cooperation in high-energy physics.[47] The IPCC mentioned earlier was instead set up with the intention to assess knowledge about climate change and provide advice for policy makers.[48] The challenges of global energy supply evidently require bringing together competencies from natural science, technology and the social sciences on an unprecedented scale.[49] The complex interplay between national and international aspects of science is considered in fields as diverse as psychology and molecular biology.[50] A specific aspect of this interplay is the differing

[45] See (Thiering 2009). See also (Foley 2010; Coupland 2010).
[46] See chapters 27 and 28.
[47] See chapters 28 and 29.
[48] See chapter 31.
[49] See chapter 30.
[50] See chapters 26 and 29.

roles of science policy together with its cultural, political, economic and military motivations.

24.9 Nuclear Physics and the Emergence of Big Science

One example for a contingent scientific discovery leading to a large-scale societal transformation was the insight into the feasibility of nuclear fission which was achieved by Otto Hahn, Fritz Strassmann and Lise Meitner in 1938.[51] It amounted to the discovery of a new way of harvesting energy from matter.[52] The military and economic impact of this discovery, in connection with the economic, political and military catastrophies of the twentieth century, fostered the worldwide establishment of Big Science.

Nuclear energy is unique in being the only significant source of energy not of solar origin. It would not have been possible without basic science and its unpredictable consequences.[53] Its economic and military significance today, however, is due to a targeted industrial revolution, as demanded by those concerned with the climate challenge.[54] This targeted industrial revolution may go back as far as the Roosevelt plan in the Great Depression, but gained momentum only with the emergency situation of World War II and the Manhattan Project to produce the atomic bomb.

This case shows a particular pathway along which a by-product of sociocultural evolution—atomic science—may lead to socioepistemic evolution. We call this path the "Manhattan Path," turning basic science to military and civil use via a gigantic engineering venture. It created not only a new technology, but also a new kind of socioepistemic complex of knowledge, technology and social structures, which, for all we presently know, is here to stay whether we like it or not. Given the dangers of even natural radioactivity for human life, the technology is intrinsically dual-use. Even if we were to eliminate the technology, the knowledge about nuclear explosives would stay with us and can easily be reproduced.

Also, the enormous quantities of radioactive materials remain with us in any case: the global stockpile of highly enriched uranium is about 1800 metric tons (IPFM 2007, 7) and each year about 10,000 metric tons of spent fuel are discharged from nuclear reactors worldwide (Feiveson 2007). And the military industrial complex, as an outcome of the Manhattan Path, is also here to stay: the five biggest defense companies in the United States employ more than half a million people and generate over 80 billion dollars per year (Hennes 2003).

Since the knowledge they produce can no longer be eradicated or even confined, it can only be controlled if further knowledge is developed, for instance,

[51] See (Hahn 1968, 150–157; Lewin Sime 1996, 161 ff.; Morgenweck-Lambrinos and Trömel 2000; Kant 2002, 88–92; Sexl and Hardy 2002, 88 ff.; Lemmerich 2004).
[52] See chapter 27. See also (Hennes 2003; Lavoy 2003; Feiveson 2007; IPFM 2008a).
[53] Thomas Kuhn discusses in detail the difference between basic and applied science in (Kuhn 1959).
[54] See chapter 31.

about political mechanisms, about possibilities for cooperation in alternative energy scenarios, and also about the dynamics of national pride.

In fact, only control by means of second-order knowledge can serve as a regulative of the spread of knowledge with dual use potential. But such second-order knowledge comes in the form of technical control and in terms of global regulations. It means to recognize the liquid quality of knowledge, seaping through any barrier. Confinement of knowledge by secrecy can ultimately only have a retarding effect. Such delays may, however, be important for creating windows of opportunities for alternative scenarios, for example, keeping Iran from acquiring atomic weapons long enough to find either a political or technical solution to its energy problems.

24.10 High-Energy Physics as an Example of Impartial Big Science

Like nuclear technology, high-energy physics emerged as basic science that at some point gave rise to unpredictable spin-offs.[55] High-energy physics is essentially the science of subatomic particles, an expensive venture with little immediate economic or social impact. Higher and higher energies are required to penetrate deeper into the structure of matter, and hence, larger and larger facilities are needed. The huge European laboratory CERN in Geneva, set up after World War II, is one of the best known examples.[56] CERN demonstrates the possibility of large-scale international cooperation on knowledge production under the boundary conditions of an absence of immediate political, military or economic implications. Not least for this reason, it has become a test ground for a new global knowledge infrastructure. The Web was invented at CERN, grid computing is being developed at CERN, and the open access movement was initiated at CERN. CERN illustrates another pathway to socioepistemic evolution.

In spite of the enormous investment in this institution, the significance of its ongoing knowledge output for fundamental physics, its role as a driver of information technology and as a model for international scientific cooperation, it is nevertheless conceivable—for political or economical reasons—that such an institution is no longer funded.[57] Some of CERN's achievements, however, in particular the World Wide Web, can no longer be abandoned without devasting consequences. Once again, it becomes evident that large-scale knowledge production ventures tend to have irrevocable sociocultural consequences. In fact, it is hardly imaginable that the future development of the global knowledge infrastructure can succeed without the continued production of scientific knowledge.

In view of the impartiality of high-energy physics with regard to immediate economic or military interests, other than concerns of prestige, one may prefer

[55] See chapter 28.
[56] For a historical account, see (Hermann et al. 1987).
[57] See the case of the Superconducting Super Collider which was terminated for economic and political reasons in 1993 (Riordan 2000).

the “CERN Path” rather than the “Manhattan Path” to socioepistemic evolution. The question that remains open, however, is whether this experience can be transferred to other areas where large-scale knowledge production is urgently needed, for instance, in the domains of climate research and energy supply, but where—in contrast to high-energy physics—strong political and economic interests may condition or even constrain necessary knowledge production.

24.11 Climate and Energy Challenges and the Quest for Socioepistemic Evolution

There is a broad consensus that global warming represents a global challenge.[58] There is also an emerging consensus that an adequate response requires a large-scale transformation of industry within the next half century or so, a transformation that has been discussed as another industrial revolution. In order of magnitude, this industrial transformation will be comparable, at least, with the transformation of the US economy during World War II, without, however, having the driving force of a generally perceived emergency situation at its disposal. Probably the most critical element of the required industrial transformation is the future energy supply system. It will have to be developed from the present situation through various steps, each requiring new knowledge and considerable social and economic adjustments. At present, after decades of effort, the proportion of solar energy in the global energy supply is still vanishingly small, much less than 1%, although the total energy supply from the sun would suffice for all our energy needs. Nuclear energy supply hovers at around 6%; its scaling up to a significant contribution to the global energy challenge seems unrealistic.[59] The proof of principle of fusion energy remains decades away. In addition, all development processes of new technology, from the proof of principle to industrial implementation, take a long time. For instance, it took more than sixty years to go from a pilot model to the first one-megawatt power plant. On the scale of what is needed, some of the present attempts to solve the problem seem rather helpless. Biofuel, for instance, has little relevance for energy supply but a large unpredictable impact on food markets. All concepts of future energy supply must be designed and verified in light of their impact on the various biological and physico-chemical regulatory systems on earth. In short, the challenges of climate and of energy result from sociocultural evolution, but cannot be successfully addressed without significant steps into socioepistemic evolution.

In the case of the energy challenge, the need for more knowledge is particularly evident, as is the problem of its generation under the circumstances we know.[60] The energy problem is so complex that research cannot prematurely focus on a single direction. Moreover, research has to proceed with attention to technical

[58] See chapter 31. See also (Rahmstorf and Schellnhuber 2006; Rockström 2009; WBGU 2009).
[59] See (Renn et al. 2011) and chapter 30 in this volume.
[60] See chapter 30. See also (Gruss and Schüth 2008).

challenges, and it has to work with alternative generalized energy supply scenarios, which analyze the resulting systems in terms of bottlenecks. At the same time, one has to take into account the boundary conditions of scalability, sustainability and climate compatibility. The difficulty of achieving effective chemical energy storage with present technologies, for instance, is the single largest bottleneck to the widespread application of solar energy.

Some argue that what is needed is a huge concentrated international research and development effort, on the scale of the Manhattan project or CERN.[61] Possibly a new international research and development center on energy chemistry could be set up, or a single strong nation may go ahead, setting new standards. It would also be necessary to include and study past experiences with major reorganizations of energy supply systems. But the resistance of the existing energy providers to any system change will be considerable and most likely have an impact, even on the level of research. In view of the socioeconomic impact of each generalized conclusion drawn from such research, the greatest challenge is therefore to enable necessary, unbiased knowledge production on a large scale, and hence to free this pathway toward socioepistemic evolution from some of the limitations of sociocultural evolution.

24.12 Molecular Biology and Genetic Engineering as Pathways to Socioepistemic Evolution

Molecular biology illustrates yet another pathway to socioepistemic evolution.[62] Starting in the 1930s, international scientific cooperation emerged, not through central planning, but rather as a bottom-up phenomenon. A decisive role was played by a few hubs in the initially rather thinly spread network of scientific cooperation. These hubs were formed by laboratories with unique pieces of equipment or with a unique combination of personal competencies. They served as catalysts for integrating knowledge from a diverse array of disciplines. Gradually, a global research landscape emerged. Just as in the CERN case, though, the practical irrelevance of the scientific knowledge produced kept the network open for a seamless flow of knowledge and personnel. This was the golden era of molecular biology. Imagined or real opportunities for engineering and commercial applications emerged only later. This new perspective encouraged large-scale organized cooperation, such as the human genome project, but also gave rise to a new fragmentation of knowledge production due to commercial and cultural boundaries. In genomics and other life sciences, commercial opportunities and patenting have meanwhile achieved a significant impact on research communication. A survey of 3000 geneticists and other life scientists found that 44% of geneticists and 32% of the other life scientists withheld data (Blumenthal et al. 2006).

[61] See chapter 30. See also (Renn et al. 2011).
[62] See chapter 29. See also (Novotny et al. 2006; Khushf 2007).

The new socioepistemic complexes emerging in connection with the life sciences, and in particular with the possibilities of genetic engineering, confirm the insight that the creation of scientific knowledge has irrevocable consequences, in this case on the future of the biological development of our species, as well of the biological substratum on which we depend. The industrial organization of the food chain, for instance, may become critically dependent on socioepistemic complexes with their own, unpredictable behavior. This may lead to a lasting change in the economy of knowledge, and in particular, to a shift between private and public domains of knowledge. Knowledge involved in the age-old cycle of seeding and harvesting used to be public knowledge. But as seeds become products of genetic engineering, rather than public knowledge, agricultural production will become increasingly dependent on privatized knowledge subject to market economy (Mulvany 2005).

24.13 Global Health as a Challenge to Sociocultural Evolution

Diseases are not only part of our biological evolution, they are also part of sociocultural evolution.[63] They have emerged, for instance, from contact between humans and animals in domestication processes. One example is smallpox, which was transferred from rodents to humans some millennia ago in the age of the Neolithic Revolution. Today global traffic, global nutrition chains and global inequalities in living conditions have set a new stage for the emergence and spread of bacterial and viral diseases. Diseases may constitute challenges that affect societies and economies on a global scale, even if they do so in extremely different ways in different parts of the world. Knowledge produced in the traditional mode, that is, as a by-product of sociocultural evolution, by basic research and market-driven innovations, may turn out to be inadequate to cope with these challenges. The global pharmaceutical market, for example, is dominated by the production of drugs for the "First World."

The challenges of the major diseases of the developing countries, such as tuberculosis, malaria and AIDS, are not only economic in character, they are also challenges for the production and transmission of knowledge. It is an evident truth that millions of HIV sufferers in developing countries cannot afford drugs at the current price level of the First World market. What is less well known is that pharmacological research and industry has for decades failed to generate the very knowledge for producing urgently needed drugs that might help to eradicate the major diseases of the developing countries. Among the 1400 drugs licensed in the last decades of the twentieth century, just three were for treating tuberculosis, four for malaria and thirteen for all the neglected tropical diseases together, whereas 180 were approved to treat cardiovascular diseases.

Such neglect begins to take its toll. In the case of tuberculosis, the knowledge for diagnosing and vaccination is about a century old and has not been substan-

[63] This paragraph draws on (Kaufmann 2008, 2009). See also (Benatar et al. 2005).

tially augmented since this time. While knowledge about how to treat this disease has not progressed, the disease itself has. New forms of multidrug resistant tuberculosis have evolved. Without making significant progress in drug development, the first decade of the twenty-first century will see 100 million cases of multi-drug resistance tuberculosis leading to 20 million deaths. This is a global challenge. There are no health sanctuaries; the disease has returned again to Europe. Among the twenty countries with the highest rate of multidrug resistant tuberculosis infections, fourteen are European. New forms of knowledge economy are needed to create the required knowledge as well as the structures for its transmission and appropriation. Incipient forms of this knowledge economy comprise the acceleration of the admission procedures for drugs relevant to developing countries, new patent legislation tuned to social rather than economic relevance, and "debt for health" policies aimed at fostering the development of health systems in poor countries. It is important to realize, however, that knowledge is neither a raw material nor a commodity that can simply be produced and brought into circulation at will.

The examples discussed so far have illustrated that the great challenges of humanity confront us with a structural deficit of knowledge. The existing modes of knowledge production and dissemination will probably be insufficient to cope with these problems. While socioepistemic complexes make the world as we know it increasingly dependent on scientific knowledge, they may nevertheless be incapable of delivering the required knowledge. Hence, socioepistemic evolution confronts us with a sheer unmanageable complexity of societal and epistemic interdependencies and with new opportunities to cope with this complexity. Its relation with a further-going globalization of knowledge is evident, but many other features are still unclear. What is clear, however, are its demands on a global knowledge infrastructure.

24.14 Toward a Global Knowledge Infrastructure

In our review of current trends in the globalization of science, we therefore finally address the developments toward a global information infrastructure, which is made possible by the new information technologies.[64] It was already envisaged in the early 1960s, with Ted Nelson's idea of a global hypertext, to potentially represent the collective knowledge of humanity in a new way, as mutually linked texts. It was realized only in the late 1980s, when the World Wide Web was developed—initially as a communication platform for physicists. Only then did the general idea meet with the technical competencies to realize it.

The Web offers a completely new way of representing knowledge. Information provided by single individuals can have an unprecedented worldwide impact. As Wikipedia and other projects illustrate, the Web allows for an equally unprecedented cooperative scalability, enabling the cooperation of thousands of individuals on the production of knowledge. The Web offers nearly universal connectivity, in

[64]See chapter 32.

principle linking every document with every other document. The Web has exceptional plasticity, allowing the available information to be corrected or reorganized quickly. The Web allows information to be found quickly, and it has a very low latency such that the production and dissemination of information are no longer separated by large time intervals. Today's social, economic and scientific reality has become unthinkable without the Web. In principle, for the first time in history, it allows for a global, dynamic representation of human knowledge with a strong, self-organizing potential. The universal access to information that it offers may thus serve as a significant catalyst for a globally connected and well-informed public opinion, serving as a driver and corrective for political and economic decision making.

However, the Web is also characterized by the fact that hardly any of these potentials are actually realized in its present implementation. There are even risks that it will degenerate more and more into a platform where information is advertised and commercialized, rather than being made openly available and effectively interlinked with other information. Visions such as those of the Semantic Web or open access to scientific information and cultural heritage are far from being realized. And what is actually needed to realize a global knowledge infrastruce goes far beyond these visions: an Epistemic Web, a Web optimized for the representation not just of information, but also of knowledge.

The Web as a new socioepistemic complex is thus no different in principle from the other such complexes we have been considering. Born as an unexpected by-product of sociocultural evolution, it has created a reality which can no longer be imagined without it, and it has opened up a new route into socioepistemic evolution. As with the other cases, the Web confronts us with technical problems, such as bandwidth and speed, as well as with social problems, such as the so-called digital divide, the unequal distribution of Internet access in the world. But all socioepistemic complexes also confront us with a political challenge, not only to employ knowledge to shape our world, but also to shape a world in which the scientific knowledge that is urgently needed can be produced and made available to whoever may best put it to use. In the case of the Web, however, there is yet another dimension. In view of the interaction between structures of knowledge and the media serving for its external representation, it is to be expected that the Web, as a medium with radically new properties, will have a profound impact on the future organization of scientific knowledge as well. In order to assess this potential, one has to take into account the complex architecture of this knowledge and its liability to change in the process of globalization.

24.15 Science as a Medium of Reflection for a Globalized World

We have stressed above that, even in disciplinary science, reflective thinking has played a decisive role in guiding reorganizations of theoretical and institutional structures made necessary by the accumulation of new knowledge. In dealing with the grand challenges of present science and technology, such as energy and climate problems, with a future information infrastructure or with the issues raised by global health and genetic engineering, reflective thinking may take on a novel and even more central role. It will have to reveal some of the implicit assumptions through which basic science depends on past and present contexts, assumptions that are not easily visible in the canonical disciplinary accounts and whose tacit acceptance may represent a hindrance to deeper insights, in particular when contexts are changing.

Making a reflective approach part and parcel of scientific practice to a far greater extent than is presently customary will also be crucial for regaining intellectual autonomy with regard to those large-scale socioepistemic complexes emerging in the process of socioepistemic evolution. The systems of knowledge associated with them are much more heterogenous than those familiar from the classical disciplines, not only spanning various of these disciplines but also comprising complex social and economic structures as well as power relationships that are rarely made explicit. Competence in governing these socioepistemic complexes is hence typically distributed over various levels of intellectual and political interactions. These interactions are plagued by the familiar difficulties of interdisciplinary cooperation and the incompatibilities between scientific and political agendas.

A more widespread acceptance of a reflective approach to science, making explicit its historical and epistemological premises as well as its susceptibility to political and economic influences, may help to address these difficulties. Developing and spreading such an approach may, however, also be associated with at least partially reorganizing the primary, first-order knowledge content of the sciences and thus ultimately transcending classical disciplines. It may indeed turn out that mastering the intellectual and political challenges of socioepistemic complexes requires bringing together large, multidisciplinary conglomerates of knowledge and meta-knowledge. It could also turn out to be useful to identify those smaller units of knowledge that may serve as starting points for their reorganization.

Hints at such a development are evident in the new forms of organizing knowledge emerging in the context of the Web, illustrating how this new medium may transform science in future globalization processes. Remarkably, some of the most effective forms of organizing knowledge on the Web actually go back to traditions preceding the establishment of the disciplines, such as the encyclopedia tradition revived by Wikipedia or the cosmographic tradition, organizing knowledge according to space, revived by Google Earth and other geographic information systems. But in spite of this rather old-fashioned appearance, their innovative features correspond precisely to the expectations formulated above, displaying information in smaller units and larger contexts at the same time, and making it more flexible and more susceptible to reflective change by exposing it to a global, interactive evaluation. There are and will be other models of organizing knowledge, making even more effective use of the interactive features of the new medium. But it is, of course, hard to predict in detail which epistemic models of future science might result from the encounter of the grand challenges described above and the potentials offered by the new medium.

The parallelism between today's Internet revolution and the printing revolution of the Renaissance has often been emphasized. It is, however, less conspicuous to what extent this revolution does not just represent a technological breakthrough, but also challenges the structures of knowledge organization which may have to be partly reinvented in light of the novel potentials rather than just being translated into the new medium. The analogy of our present situation with the age of the Scientific Revolution is, however, not limited to that of a comparable innovation of media. It rather seems that another comparable feature of both historical moments is represented by the prominence of great challenging problems requiring new forms of knowledge integration. In the early modern period, the challenging objects of science were generated by the great engineering ventures which made it necessary to assemble all knowledge resources available, from Greek mathematics to the practical experience of contemporary engineers.

In our period, the grand challenges are instead represented by the problems encountered in the aftermath of the great civilizatory ventures (and their pitfalls) initiated in the early modern period. Today's challenges no longer concern just the local fate of city states but—via the grand socioepistemic complexes emerging with socioepistemic evolution—also unavoidably the global society. Characteristically, the overarching perspective required by some of the outstanding challenging problems of today is therefore no longer one of infinite horizons and new worlds, but one focusing on the limits and the intrinsic complexity of systems, whether these are of an ecological, societal, cognitive, or cosmological nature. Compared to the early modern period, the main concern of the present is no longer one of universalizing the local, but of localizing and contextualizing the supposedly universal.[65] We are no longer compelled to categorically segregate culture from nature but be able to realize that these categories may be inescapably mingled, and not just by setting each other limits or standards. In the Renaissance the grand challenges were addressed by outstanding intellectuals who were unrestricted by academic or guild traditions, by great individuals such as Leonardo, Kepler or Galileo. While the historical moment of such universalist thinkers may have passed, there can nevertheless be little doubt that, at present, we need no less courage to transgress established boundaries, both on the individual and institutional levels, to explore the potential of the knowledge resources divided by these boundaries and to exploit the potential of science as a medium of reflection for a globalized world.

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[65]See (Morin 2001; Sloterdijk 2005; Tomasello 2009; Habermas 2011; Sloterdijk 2011; Hessel and Morin 2012). See also chapter 25 in this volume.

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