From the History of Science to Geoanthropology

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Abstract: To understand the dynamics and trajectories of the Anthropocene, the single most crucial parameter of investigation is time—specifically, the interconnections and friction between multiple timescales and temporal processes. This essay outlines a possible role for the history of science in understanding the Anthropocene. The notion of the "Anthropocene" entails different historical horizons being banded together—in particular, *longue durée* transformations and the now-accelerating environmental and socio-epistemic changes. But the challenge of the Anthropocene for the history of science lies not only in new questions, topics, and methodological approaches: the history of science itself may gain new opportunities to use its insights and reflective potential to encourage innovative forms of scientific knowledge production. The essay argues that we need a new transdisciplinary, transformative science in order to understand the techno–Earth System from an integrative perspective. This new science of "geoanthropology" should study the technosphere as part of the techno–Earth System by integrating different disciplinary perspectives.

THE ROLE OF HISTORY

By means of science and technology, humans have radically changed the general conditions for life on our planet.[1] The atmospheric chemist and Nobel Prize winner Paul Crutzen reinvented a term for the comprehensive nature of these changes—the "Anthropocene" (earlier also used by Eugene Stoermer)—marking a new human-dominated geological epoch in Earth's

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[1] This text is partly based on Jürgen Renn, *The Evolution of Knowledge: Rethinking Science for the Anthropocene* (Princeton, N.J.: Princeton Univ. Press, 2020); Renn *et al.*, "Towards a Max Planck Institute for Geoanthropology," unpublished white paper (Max Planck Institute for the History of Science, 2021); and Renn, "Metamorphosis of the Technosphere: A Tribute to Dirk Messner, Intellectual, Politician, and Friend," in Transboundary Cooperation and Global Governance for Inclusive Sustainable Development, ed. I. Scholz, B. Busse, and T. Fues (Baden-Baden: Nomos, 2022), pp. 231–241.

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history.[2] The concept of the Anthropocene stands for the systemic nexus between climate crisis, biodiversity crisis, and environmental crisis. In what follows, I will expand on how it reveals a newly emerging necessity to orient intellectual comprehension, scientific research, and political action toward the behavior of interoperational systems and the temporal processes that underlie them.

What can the Anthropocene possibly mean for a history of science or for history in general? What new perspectives does it entail? Will it just lead to the next fashionable turn? In my view, the history of science can make a decisive contribution to the understanding of the Anthropocene, but only if it overcomes the one-sidedness of approaches that still tend to focus on highly localized narratives or on fashionable viewpoints. In other words, the theme of the Anthropocene is also an opportunity for the history of science to break out of its occasionally scholastic or postmodern fragmentation in order to confront a much larger picture.

The scholarly practices of history and historiography have a very long tradition, but now we have to rethink and revise them in more profound ways than ever. Pathbreaking contributions to this rethinking have been made by Dipesh Chakrabarty, John McNeill, Julia Adeney Thomas, and other historians.[3] There are two reasons why such rethinking is also necessary for the history of science: embedded within a broader history of knowledge, it has become increasingly relevant to our current predicament; and its traditional scholarly practices have turned out to be inadequate to meet the current challenges.

First, historical studies have become more relevant than ever in the Anthropocene as a resource of knowledge on which we must draw in guiding our present and future actions. Past, present, and future are more entangled than we had realized because our present and future options for action are deeply shaped by path dependencies that operate on a planetary scale, including those we are creating here and now. The history of science is in a position to make a particularly relevant contribution to understanding the pathways that have led us into the Anthropocene. What has been the role of knowledge in the dynamics of cultural evolution? Why has global human society developed a growing dependence on the production of scientific knowledge that contributes to both the conditions for its survival and the dangers of its demise?

In ancient urban societies, the evolution of knowledge as an aspect of cultural evolution gave rise to science that has—since the so-called Scientific Revolution of early modernity and through globalization processes—turned from a marginal activity into a driving force of capitalist expansion and colonial expropriation, as is strikingly illustrated by Iva Peša's essay in this Focus section. Just as cultural evolution eventually developed from a marginal aspect of biological evolution into an evolutionary process in its own right, the growing integration of science into economic practices has given rise to new dynamics with planetary consequences, particularly since the inception of the use of fossil fuels in the Industrial Revolution.

The combination of economic, technological, and scientific developments may be characterized as an even further accelerated and novel form of cultural evolution: as an "epistemic evolution." Just as biological evolution has been shaped—at least since the Neolithic Revolution—by

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[2] See Paul J. Crutzen and Eugene F. Stoermer, "The 'Anthropocene,'" *Global Change Newsletter*, 2000, *41*:17–18; and Susanne Benner, Gregor Lax, Crutzen, Ulrich Pöschl, Jos Lelieveld, and Hans Günther Brauch, eds., *Paul J. Crutzen and the Anthropocene: A New Epoch in Earth's History* (Cham: Springer, 2021).

[3] See, e.g., Dipesh Chakrabarty, "The Climate of History: Four Theses," *Critical Inquiry*, 2009, 35:197–222; J. R. McNeill and Peter Engelke, *The Great Acceleration: An Environmental History of the Anthropocene since 1945* (Cambridge, Mass.: Harvard Univ. Press, Belknap, 2014); and Julia Adeney Thomas, Mark Williams, and Jan Zalasiewicz, *The Anthropocene: A Multidisciplinary Approach* (New York: Polity, 2020). See also the contributions to Katrin Klingan and Christop Rosol, eds., *Technosphäre* (Berlin: Matthes & Seitz, 2019); and Jürgen Renn and Bernd Scherer, eds., *Das Anthropozän* (Berlin: Matthes & Seitz, 2018).

cultural evolution, cultural evolution is becoming ever more dependent on science and technology in an accelerated process that is driven by feedback loops between the material economy and the economy of knowledge.

Second, traditional scholarly practices have turned out to be inadequate to understand these dynamics because the current challenges are due to a newly forged entanglement of global human history with Earth history. This entanglement involves systemic and quantitative aspects that are rarely taken into account in the prevailing approaches to history writing. We need to cope with an unprecedented and highly dynamic complexity that is hard to fathom in terms of our familiar argumentative structures or conceptual systems, let alone the so-called "narratives" dominating in the humanities.

THE TECHNOSPHERE AS A BORDERLINE PROBLEM

Human societies are coupled with the Earth System through dynamically changing and locally diverse ecological conditions, metabolic flows, and technical infrastructures that, in their totality, make up an Earth sphere in its own right: the technosphere. This technosphere is now functionally equivalent to other geospheres such as the atmosphere, the hydrosphere, and the biosphere. But what exactly makes the wide-ranging set of infrastructures and technologies a "technosphere" and what are its defining features? In a trailblazing paper, the Earth scientist Peter Haff claimed in 2014 that the technosphere operates quasi-autonomously and summarized these autonomous dynamics in six rules. The rules of "inaccessibility" and "impotence," for instance, state that "large components of the technosphere cannot directly influence the behaviour of their human parts" and that "most humans cannot significantly influence the behaviour of large technological systems." The rule of "provision" states that "the technosphere must provide an environment for most humans conducive to their survival and function."[4]

Haff arrived at these characterizations, which shimmer between resignation and a residual trust in some bleak form of salvation, by mimicking a method of statistical physics. The method adopts an intermediate level of resolution for a "coarse-grained" description of a system in which only collective behavior matters, such as in describing highway traffic by considering only the density of cars on the road, not the individual cars. In more recent writings Haff emphasizes the challenges posed by ongoing technological acceleration and arrives at an even more skeptical assessment of our planetary predicament—one that will spell disaster unless we are able to slow this accelerated development.[5]

But how realistic is this assessment and how useful is the underlying description of the technosphere? To what extent does this technosphere concept prolong the problematic conception of technology as a device used to elevate oneself above and apart from nature, imposing its own logic on it, rather than considering how technology stands as an intermediary between humans and nature and, in that way, as something that occupies a flexible and negotiable position between them? The former position pervades both affirmative and critical assessments of technology from Plato to Heidegger, and the latter has been emphasized, within the European tradition, by thinkers such as Hegel and Marx, although it goes back to a much older and broader tradition. In this essay I would like to comment briefly on these conceptual demarcations of the technosphere's role, given its significance for our understanding of the Anthropocene and for our future prospects as a species confined, for the time being, to a single planet.

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[4] Peter K. Haff, "Humans and Technology in the Anthropocene: Six Rules," *Anthropocene Review*, 2014, *1*:126–136, on p. 126.

[5] Peter K. Haff and Jürgen Renn, "'Was Menschen wollen' ist keine Richtschnur dafür, wie die Welt tatsächlich funktioniert," in *Technosphäre*, ed. Klingan and Rosol (cit. n. 3), pp. 26–46.

In earlier writings on this issue I suggested an alternative concept for the new human-made Earth sphere, the "ergosphere."[6] I conceived of it as a sphere of human "work" (Greek *ergon*) characterized by the transformative power of human labor, with regard to both the global environment and humanity itself. It encompasses the cumulative effects of human interventions, including technology and infrastructures, but also the impact of works of science and art, all of which express human needs, desires, fears, hopes, and insights. In contrast to Haff's claim that the technosphere is essentially autonomous and preserves itself like some kind of superorganism, I emphasized how the ergosphere is open to different ways of shaping the relationship between humanity and its planetary home. The ergosphere concept thus pays tribute to the transformative power of human labor and offers more room for taking into account processes and practices negotiated politically and scientifically.

It is true that the development of technology is accelerating, with consequences that are sometimes unforeseeable and often uncontrollable. There are also planetary limits that we should avoid overstepping lest we risk the collapse of societies. And there is the immense heterogeneity of humanity and its asymmetries of power, which, as Haff writes, make it difficult for most humans to influence the behavior of large systems. He is also right when he claims that the technosphere, as a complex regulatory system, is self-organizing. Its self-reproduction by the renewal or exchange of its human and technological components is controlled by structures—societal or technological—that tend to persist through such changes.

But we should not forget that these structures may change gradually in an evolutionary process or, under certain circumstances, even break down. As a consequence, the resilience and long-term stability of the technosphere is not guaranteed just because it can self-organize. Instead, it seems to me that the future is not predetermined: the new Earth sphere has some plasticity, and it can even be shaped by our interventions to become favorable to the flourishing of human cultures and also to global cooperation—provided that we get a better handle on its dynamics.

The concept of the technosphere, it turns out, has been widely used, without any strict adherence to Haff's six rules—which implies that a largely autonomous system is governing us, with little chance of being governed by us. This leaves room for, and perhaps even necessitates, a new definition of the technosphere that does justice to the actual use of the term—and also to the insights of history, political science, and anthropology that I have attempted to capture with the notion of the ergosphere.

Rather than deriving the properties of the technosphere from the viewpoint of physics, I propose to consider the technosphere as instead a borderline problem of different perspectives and disciplines.[7] By this, I mean that the technosphere can be adequately described only by taking into account and bringing together different systems of knowledge, just as one can understand humans only when considering them as biological, cultural, social, and indeed technological beings. In the same way that digital computing can be understood only as the result of addressing borderline problems across different fields (e.g., solid state physics, mathematics, information science), the concept of the technosphere belongs, in equal measure, to diverse fields of knowledge whose methods need to be brought together if we are properly to appreciate it as a borderline problem.

This integration may come with major repercussions for the different frameworks involved in the process, because borderline problems require different perspectives to be related to each other, not in an abstract or metatheoretical way but in terms of a concrete challenge. This is clearly

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[6] Renn, *Evolution of Knowledge* (cit. n. 1), Ch. 6.

[7] For a discussion of the notion of borderline problems see *ibid.*, pp. 81, 126–127.

the case for the technosphere. As an Earth sphere, it falls under the domain of the Earth System sciences; but as a human construct, it also falls under that of the social and human sciences. This poses a methodological challenge, as it raises the question of the relationship between the analytical, experimental, and systemic accounts of the sciences, on one hand, and the more narrative and interpretative approaches of the humanities, on the other. To illustrate this challenge, I will take a brief look at the techno–Earth System (i.e., the Earth System extended by the addition of the technosphere) from the perspectives of the natural and the human sciences, focusing in both cases on its temporal dimension.

THE TECHNO-EARTH AS A COMPLEX ADAPTIVE SYSTEM

The Anthropocene as a concept is also the result of a new kind of Earth science: a transition from geology to Earth System science whereby our planet can be understood as a nonlinear complex system with many feedback loops. According to this new understanding, the Earth System is not only subject to uniform change processes but can also achieve tipping points that lead to such catastrophic changes as Snowball Earth events, which have happened several times in the past. This is why some also speak of a "new catastrophism."[8]

It has long been known that the biosphere has played a crucial role in such events since the beginning of its existence. Earth System scientists have realized that this may also apply to the technosphere. More than ever, we have made ourselves dependent on our understanding of the techno–Earth System as a complex adaptive system. Such a techno–Earth System view provides a conceptual entry point for understanding the Anthropocene as a transition that encompasses processes of biophysical and geochemical change and their close interdependencies with historical and societal developments.

As such systems become more complex, with countless reciprocal feedbacks between biology and culture, earthly materials and history, they also become more liable to systemic risks. Indeed, the maintenance of complexity typically requires ever more seamless interactions among different subsystems and ever more physical and social energies. New types of risks emerge from the propagation of seemingly harmless local events within global network structures and may lead, in some cases, to system collapse. This may be illustrated by historical and recent events such as the global financial crisis of 2008 and the present Covid-19 pandemic.[9]

Understanding the temporal behavior of complex systems dynamics poses major challenges to their conceptualization and mathematical description—but also to data acquisition, analysis, and simulation. Much can be learned here from evolutionary theory because of the way it accounts for the interplay between different complex adaptive systems, for path dependencies, tipping points, lag times, and the emergence of temporal regimes.

According to a recent view of biological evolution, two factors play an important role: regulatory mechanisms governing the developmental dynamics of an organism, discussed under the headings of gene regulatory networks and "evo-devo"; and the role of the environmental feedbacks brought about by the organisms themselves, which is discussed under the heading of "niche construction"—as in the famous example of beavers constructing their dams.[10] From

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[8] See, e.g., Peter Ward and Joe Kirschvink, *A New History of Life: The Radical New Discoveries about the Origins and Evolution of Life on Earth* (New York: Bloomsbury, 2015).

[9] Leopoldina Working Group, "Coronavirus-Pandemie—Die Krise nachhaltig überwinden," Ad Hoc Statement, 13 Apr. 2020 (Halle: Nationale Akademie der Wissenschaften Leopoldina, 2020), https://www.leopoldina.org/publikationen/detailansicht/publication/coronavirus-pandemie-die-krise-nachhaltig-ueberwinden-2020/ (accessed 21 March 2021).

[10] See Manfred D. Laubichler and Jürgen Renn, "Extended Evolution: A Conceptual Framework for Integrating Regulatory Networks and Niche Construction," *Journal of Experimental Zoology Part B: Molecular and Developmental Evolution*, 2015, 324:565–577.

the perspective of cultural evolution, both are obviously crucial factors. The culture of human societies is not simply a collection of memes, some of which are handed down and others not, but is subject to complex regulatory mechanisms that are traditionally the subject of the cultural and social sciences.

Only a consideration of these manifold regulatory structures of social systems makes a description of cultural development realistic, without reducing it to simple analogies of mechanisms of transmission and selection of single cultural elements. And, of course, human culture essentially consists in niche construction—that is, in the construction and transmission of material environments, from architecture through infrastructures, production systems, and technology to the symbolic systems on which the transmission of knowledge, and scientific knowledge in particular, is based.

From the perspective of such an approach to extended evolution, it may be possible to investigate the dynamic transformations of the techno–Earth System and, in particular, the interconnections and frictions between multiple timescales and temporal processes. These can be found in the concrete evolution of subsystems, each guided by different but intersecting *timescales*, in the coupling of different, often asymmetric, *time horizons* between sociotechnical and biophysical systems (e.g., energy transitions and climate inertia), thereby revealing the criticality of time—and also in the sense of the *time left* for meaningful action.

THE TECHNO–EARTH SYSTEM AND HUMAN TIMESCALES

Different time regimes are, of course, also characteristic of human societies *per se*. Indeed, as we can learn from Norbert Elias, time conceptions and practices of timekeeping are a reflection of the ways in which societies coordinate relationships and interactions among their members and with their environments, mediated by the historically available media and technologies supporting these interactions.[11] But the temporal dimension is even more deeply inscribed into human existence, characterized as it is by the cycles of birth, life, and death and the relation between individual life experiences and those of the species. This farther-going anthropological time experience, we might say, even has a cosmological or existential meaning, because it provides a fundamental frame for positioning our individual and collective existences within the world at large. At first glance, these two temporal dimensions seem to be in conflict with each other: one culturally malleable and historically changing, the other perhaps universal.

Beginning with the first, evidently historically malleable, aspect: our ways of acting and thinking are shaped by the historically available material and symbolic culture, which must be considered an integral part of the regulatory structures of human societies. Abstract concepts such as time could only be formed on the basis of certain shared experiences and their representation by material tools, artifacts, and symbol systems. It is not self-evident that the experience of temporality in music, the experience of temporality during a journey, or the experience of temporality in a generational shift should be covered by an overarching concept of time. Instead, the development of such a concept depends on two essential prerequisites: the occurrence of real processes that mediate between different domains of temporal experience and the possibility of representing such experiences in a medium that allows reflection thereon.

The epoch of the Anthropocene confronts us in an even more dramatic way with the confluence of multiple times—the times of shrinking glaciers or drawdowns of CO_2 concentrations to the time of the sudden collapse of a carbon market; the time in which a virus may have spread from a bat to a pangolin to a human in a Chinese wet market to the time cast by an "era

[11] Norbert Elias, *An Essay on Time* (1984), in *The Collected Works of Norbert Elias*, Vol. 9 (Dublin: Univ. Dublin Press, 2007).

of pandemics," as Dipesh Chakrabarty has called it.[12] These manifest themselves in locally diverse ways that also turn out to be temporally diverse ways. For our social and political lives, but also in our historical accounts, we still have to find the cognitive means and cultural abstractions capable of dealing with the multitude and complexity of social time in the Anthropocene.

The anthropological time dimension, in the sense of the presence of existential conditions, conflicts, and experiences of human life in the memories of human societies, not only raises even deeper questions concerning a historical understanding of the human predicament in the Anthropocene but may also help us to confront this multitude in a productive way, without reducing its complexity.[13] These memories even point to a historical layer that may serve as a resource for addressing the intellectual and political challenges of the Anthropocene and, in particular, for recognizing potentials for the alliances that are urgently needed to address both of these challenges. From the perspective of this anthropological dimension, the great varieties of social time do not just amount to a hallucinatory flicker reflecting the multitude of histories taking the place of the one grand master narrative but without its outdated collective binding force. Instead, these histories may gain their own, fresh, binding force from the common reference point of species history—without being reducible to different versions of one underlying origin myth by negating the violent ways in which classes, races, and genders have been treated unequally throughout the history of civilization.

On the contrary, the memories of human societies can be read as a rich treasury of different ways of taking issue with unresolved conflicts that have ultimately driven us into the Anthropocene crisis. In fact, as much as these memories bear the mark of repressing these conflicts, they also bear that of forms of resistance against widely spread tendencies to destruction and self-destruction, ecocide and ecosuicide. From this perspective, these testimonies of the past may acquire the role of historical allies in the struggle to turn the Anthropocene from a crisis into an opportunity, an opportunity to strike a better balance between humans and the planet they inhabit. Bringing together the seemingly conflicting viewpoints of social time, standing for the multifaceted histories of human societies, and anthropological time, standing for the overall history of the human species on this planet, therefore opens the opportunity for a therapeutic moment in doing history—not from an external, allegedly superior, enlightened or teleological position, but from inside the analytic process of the species itself.

In summary, the Anthropocene as a new geological epoch forces us to think geological and historical time together as a new form of planetary time. Natural history and human history thus become entangled in new ways. Realizing that the Anthropocene needs to be addressed as an urgent crisis, we have to integrate physical, historical, and evolutionary time in order to identify the critical time zones marked by the intrinsic time-behavior of the complex techno–Earth System. In other words, history and other human sciences have to be brought together with Earth System science. And, finally, taking the Anthropocene as an opportunity to establish a sustainable relation between our species and the planet requires us to integrate the social time of human histories with the anthropological time dimension that belongs to each of them, thus giving rise to a multifingered species time, a reference point for any kind of history suitable as a resource for the alliances we need to build in order to cope with the challenges of the Anthropocene.

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[12] Dipesh Chakrabarty, "An Era of Pandemics? What Is Global and What Is Planetary about COVID-19," *Crit. Inq.*, https://critinq.wordpress.com/2020/10/16/an-era-of-pandemics-what-is-global-and-what-is-planetary-about-covid-19/ (accessed 6 Oct. 2021).

[13] See, e.g., Aleida Assmann, *Cultural Memory and Western Civilization: Functions, Media, Archives* (Cambridge: Cambridge Univ. Press, 2012); Jan Assmann, *Cultural Memory and Early Civilization: Writing, Remembrance, and Political Imagination* (Cambridge: Cambridge Univ. Press, 2011); and Klaus Heinrich, *Anthropomorphe: Zum Problem des Anthropomorphismus in der Religionsphilosophie* (Basel: Stroemfeld/Roter Stern, 1986).

THE FUTURE OF HISTORY: GEOANTHROPOLOGY

To conclude, let me comment briefly on the overarching project that aims to establish a new transdisciplinary venture under the label of geoanthropology, of which history in the sense of a new science of time as I have tried to sketch it will be a critical component.[14] Partial improvements in environmental policy, economic incentives, and sociotechnical transformations are inadequate to cope with the systemic nature and the fundamental scale of the dynamics of the Anthropocene crisis. Improvements at one end risk becoming aggravations at other ends. To reduce the risk of systemic collapse of basic ecological, economic, and societal functions, it is therefore vital to understand better the configuration and dynamic evolution of the crucial nexus between human agency and the Earth System in its complex, highly interactive, interdependent, and time-critical nature.

The proposed science of geoanthropology responds to this challenge by merging an updated version of Earth System research (the *geo*, including the *bio*) with cultural theories and histories of socio-material, energetic, and informational flows (the *anthropos*) by forming a new discipline (the *logos*). Through analytical and interpretative approaches, geoanthropology should study the various drivers, dynamics, and dilemmas that have led us onto an Anthropocene path and apply these insights to cope with its further unfolding and rapid intensification. Cast into a research framework that studies the complex co-evolution of natural and human systems, geoanthropology investigates the concrete human-created conditions of ongoing Earth System and biosphere destabilization, the limits of socio-ecological carrying capacities, possible system thresholds and collapses, tipping elements, and points of no return, as well as necessary socioeconomic and cultural reaction times.

This explanation needs an amendment, however. It is not the *anthropos*, as in the term "Anthropocene," as such that has accumulated immense planetary impacts and their often dire consequences. Instead, it seems more appropriate to consider the technological empowerment, sociotechnical evolution, and high carbon intensity of *certain parts* of modern humanity as the decisive origin of the dangerous dynamics now unleashed. (I therefore fully agree with Iva Peša's quest to engage in debates about capitalism and colonialism to comprehend the inequalities of the Anthropocene).[15] In that sense humans are a cultural and political species, but most importantly they are a "technological species," able to construct their own niche by using tools, transforming matter, and increasingly controlling the energy pathways that sustain them. In recent times, these earlier forms of human niche construction have resulted in the emergence of a qualitatively new planetary sphere, described by the technosphere concept introduced earlier.

As mentioned at the beginning of this essay, the technosphere is a key concept for geoanthropology. As an interface between humans (both individual and collective) and the geosphere (comprising all natural spheres, in our definition), the technosphere is understood here not in a narrow sense as a mere technological or technocratic entity. Instead, it is a conceptual framing of the highly amorphous network of planet-affecting technologies and infrastructures, as well as cultural, institutional, and knowledge systems, which exhibit multiple forms of agency.

The technosphere is both a catalyst of human powers and a new substrate on which a vastly expanded human population now depends. Although the technosphere might turn out to be only a transient stage, it appears to be the most decisive addition to the Earth System since the emergence of the biosphere and represents therefore not just a quantitative but also a qualitative change in both human and Earth System history. While the preindustrial *anthropos* was indeed largely embedded within the biosphere, the emergence and rapid development of the

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[14] The following is based on Renn *et al.*, "Towards a Max Planck Institute for Geoanthropology" (cit. n. 1).

[15] Iva Peša, "A Planetary Anthropocene? Views From Africa," in this Focus section.

technosphere has elevated human agency to its current, hugely outsized place in the Earth System's architecture. The aim of geoanthropology is to study the co-evolutionary system created by the addition of the technosphere to the Earth System: the *techno–Earth System*.

Finally, against this background, I want to come back to the task of defining the technosphere, not as a result of coarse-graining, which essentially reduces it to an object of physics, but as a borderline problem of the various disciplinary perspectives concerned with the multiple dynamics to which it is subjected—and thus as the challenging object of the new science of geoanthropology. Following the illuminating example of Peter Haff, I will formulate six rules that are intended to bring out these multiple dynamics:

1. The rule of the spheres: The technosphere is an Earth sphere in its own right and has global material and energetic dimensions comparable to those of other Earth System spheres.
2. The rule of entanglement: The technosphere is entangled with other Earth spheres, shaping the dynamics of a composite techno–Earth System.
3. The rule of cultural evolution: The technosphere is subject to an interplay of niche construction and cultural evolution.
4. The rule of co-evolution: The evolution of the technosphere and the evolution of the biosphere condition each other.
5. The rule of expansion: The expansive dynamics of the technosphere as an evolving complex regulatory system with virtually unlimited energy resources risks destabilizing the techno–Earth System by transgressing planetary boundaries.
6. The rule of epistemic evolution: The technosphere is subject to an interplay of global changes and knowledge evolution involving an ever-greater dependence of human societies on science and technology that contributes to its accelerated expansion but is also potentially capable of ensuring favorable conditions for the flourishing of human cultures.

The first rule defines the technosphere as a separate Earth sphere, without pretending that it is a homeostatically stable system; the other five rules specify different types of dynamics that shape its evolution as a hybrid human/nonhuman system. The second rule states that the technosphere is subject to an overall Earth System dynamics—for example, to continued human-induced climate change that may drive the system into a hothouse state or otherwise lead to the crossing of planetary boundaries. The third rule describes the continued dependency of the technosphere on the dynamics of cultural evolution, which involves niche construction, as well as the cultural, social, and economic changes interacting with it.

The fourth rule stresses the interaction between technosphere and biosphere, in the sense that humans, their domesticated plants and animals, their ecologies, microbiomes, diseases, and so forth, are, at once, components of both the technosphere and the biosphere and are thus still subject to the biosphere's laws and evolutionary dynamics. The fifth rule addresses the expansive tendencies of the technosphere. These tendencies are due to various mechanisms, such as the feedback loops inherent in cultural evolution, population growth, and access to virtually unlimited energy resources, first by tapping into fossil fuels, then by using nuclear and renewable energies. The sixth rule stresses the importance of knowledge evolution for the dynamics of the technosphere. It specifies the deeply ambivalent role of knowledge as a catalyst of its expansion and as a potential for mitigating and controlling its dynamics. Epistemic evolution may even present the possibility of a veritable metamorphosis of the technosphere into an ergosphere in which humans can still recognize themselves. In summary, these rules tell us that the plan for the future evolution of the technosphere has not been fixed once and for all. Rather, it may be changed by actively exploring the mutability of the world around us.