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Abstract

Humans play an essential role in creating the technological systems of the Anthropocene, but, nonetheless, large-scale technology – the 'technosphere' – operates according to a quasi-autonomous dynamics, summarized by six rules: (1) the rule of inaccessibility, that large components of the technosphere cannot directly influence the behavior of their human parts; (2) the rule of impotence, that most humans cannot significantly influence the behavior of large technological systems; (3) the rule of control, that a human cannot control a technological system that expresses a larger number of behaviors than he himself; (4) the rule of reciprocity, that a human can interact directly only with systems his own size; (5) the rule of performance, that most humans must perform at least some tasks that support the metabolism of the technosphere; and (6) the rule of provision, that the technosphere must provide an environment for most humans conducive to their survival and function.

Keywords

Anthropocene, coarse-graining, complexity, control, technology, technosphere

Introduction

The argument that we are living in a new geologic epoch, the Anthropocene (Crutzen and Stoermer, 2000), is usually supported by reference to the many ways in which humans appear to be impacting the planet, potentially challenging through their activity the major forces of nature (e.g. Crutzen, 2002; Steffen et al., 2007). The aim here is to emphasize another factor at play in addition to direct human impact and intentionality. This factor is large-scale technology, summarized here under the concept of the technosphere (Haff, 2012, 2013). The focus of the present paper is on the dynamics of this newly emerged Earth system (Haff, 2013), and the consequences for humans of being numbered among its parts.

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The technosphere includes the world's large-scale energy and resource extraction systems, power generation and transmission systems, communication, transportation, financial and other networks, governments and bureaucracies, cities, factories, farms and myriad other 'built' systems, as well as all the parts of these systems, including computers, windows, tractors, office memos and humans. It also includes systems which traditionally we think of as social or human-dominated, such as religious institutions or NGOs. The Haber-Bosch process and associated technologies, responsible through synthetic fixation of nitrogen and distribution of resulting fertilizers for providing about 40% of the world's dietary protein (Smil, 2002), is a specific example of a globally distributed component of the technosphere.

In the following paragraphs we abandon the apparently natural assumption that the technosphere is primarily a human-created and controlled system and instead develop the idea that the workings of modern humanity are a product of a system that operates beyond our control and that imposes its own requirements on human behavior. The technosphere is a system for which humans are essential but, nonetheless, subordinate parts. As shorthand we can say that the technosphere is autonomous. This does not mean that humans cannot influence its behavior, but that the technosphere will tend to resist attempts to compromise its function (which is defined below). The emergence of autonomous technology is a topic that has been much discussed earlier in political and social terms; see for example Winner (1977) and Ellul (1967), and, more recently, Arthur (2009) and Kelly (2010), whose works go a long way toward disabusing the notion that humans operate as independent agents in the modern technological world. Our contribution to the discussion on technological autonomy is to attempt to put certain aspects of the human relationship with technology, especially large-scale technology, on a more physical basis.

It has been argued elsewhere (Haff, 2012, 2013) that the technosphere represents a new stage in the geologic evolution of the Earth. It is a global system whose operation underpins the Anthropocene and therefore merits special attention in our attempts to understand the role of humans in a nascent geologic epoch. The property of technological autonomy relocates the basis for thinking about problems such as environmental degradation from a human-centric to a system-centric perspective. The emphasis shifts from focusing only on the human side of the equation to a consideration of the demands of the technosphere itself. We say 'demands' because autonomy has its own necessities and an autonomous system must operate in a way to ensure that it can satisfy them. Thus, an autonomous system must be able to self-solve problems that would otherwise oppose or terminate its function. For example driverless cars must be able to brake, swerve and perform numerous other maneuvers of self-control in order to navigate an urban environment (Benenson et al., 2008). At the large scale, the unplanned, undesigned and spontaneous crystallization of diverse and previously disparate elements of technology into the networked, global system called the technosphere meant there was a new player at the table whose interests would have to be considered in tandem with human interests. This is the point at which the technosphere escaped human control. We analyse the role of technology in the Anthropocene by examining basic physical principles that a complex dynamic system must satisfy if it is to persist, i.e. continue to function, and then interpret these principles as they apply to the technosphere and its human components.

Pursuing this line of reasoning may appear to drift from a direct analysis of problems of the Anthropocene, but an understanding of the underlying physical nature of the technosphere vis-à-vis its human components can help address salient problems of an Anthropocene Epoch that are mediated by technology, such as global warming. The present work does not attempt the difficult task of prescribing solutions for these problems, but focuses as a necessary first step on dynamical questions concerning the relation of humans to technology. Such analysis is timely, as the Anthropocene is being considered for official acceptance with full geologic stature (e.g. Zalasiewicz et al., 2010).

The aim here is to determine a set of basic physical rules that are expected to be true for large complex systems – and for their components, including any human components – regardless of detailed system construction or function, and on the basis of these rules to gain insight into the relationship between the technosphere and its human components. These rules do not include an equation of state; they contain no reference to the specific constitution of any system (or part) – they are not constitutive – and in consequence are not predictive except that, like conservation laws in physics, they impose constraints on system behavior. They are therefore informative about conditions humans face as they attempt to navigate the Anthropocene. Note that the rules invoked here, although general, are less crisp than principles or laws of physics, deriving more from qualitative observation than from precise quantitative experiments. They are, however, more useful descriptors of the systems to which they apply, even if at the same time more subject to revision.

Organization and constraint

As considered here a system is a collection of parts. These parts may themselves be systems. A system is *dynamic* if it does something, or equivalently, if it consumes energy. A dynamic system of many parts is *organized* if the system function can be described succinctly. Organization means that many parts work together. The collectivity of actions reduces the number of words (or bits) needed to describe what the system does, making a succinct description possible. For example, an automobile can be described as an (organized dynamic) system whose function is to transport people and goods quickly and safely along highways. For the moment we skip over the level of detail that one might employ in such a description. The implication of organization for most parts that belong to an organized, persisting system is that their behavior be consistent with the function of the system to which they belong. The qualification 'most' means that we make allowance for an occasional broken part whose inutility does not significantly impair system function – as a wobbly leg on a table does not cause a restaurant to go out of business, This requirement of consistency implies strong constraints on the behavior of system parts.

Constraints applied to non-human parts are often hard or mechanical, such as the flanges that ensure that a train remains on the tracks. Constraints applied to humans can be hard or soft. A company employee experiences the hard constraints of his office, whose walls resist penetration. The door is open, but the soft constraint of fear, for example the implicit threat that he could lose his job, suffices to keep him confined for much of the day. If he is lucky, he is subject to the softer constraint provided by incentives, for example the prospect of higher pay or, better, the implicit incentive offered by a rewarding job – he wants to be in the office because he loves what he does. Enjoyment of or pleasure in an activity may have an internal, human source, but technology often provides the means necessary for self-satisfaction, for example in the supply of materials and studio space for an artist. A host system may also offer disincentives or punishment for wayward behavior that obstructs or interferes with system function – the implicit threat of job loss for a lazy worker, execution for a murderer, court martial for a deserter from the army, suspension for a disruptive student and so on. From the point of view of the host system, the purpose of such constraints, incentives or deterrents is, in the end, to keep its human parts locked into the system so that the system can continue to function.

This line of argument can be applied to the technosphere itself. A succinct description of this system can be based upon the observation that in the pre-Anthropocene, pre-technological world the human population was perhaps 10 million (US Census Bureau, 2012). The ramp-up of technology from pre-history through, e.g., dynastic China, Rome and medieval Europe to today's global technology has led to the expansion of this population to a level approaching 10 billion today (7.2 billion in 2014), suggesting that on the order of 999 out of every 1000 humans owe their existence and their wellbeing to technological systems. A compact description of the technosphere is that it is a global apparatus that searches for, extracts, and does work with (mostly) fossil energy resources to provide support for its own existence as well as that of its essential parts, including members of the world's human population. This description partly reflects the fact that every dynamical system that has a long lifetime as measured in multiples of the timescales of its major components, such as the cycle times of corporations or governments or the usable life of buildings and other capital, must be organized or configured in such a way as to reliably find and use high quality energy to support its metabolism. Otherwise the system would have run down in a few cycle times and would not be available for us to discuss. These conditions are expected to apply to most large technological systems, as well as to the composite technosphere itself. In the following section we develop the argument that, in the technological world of the Anthropocene, most people are subject to the rules of – are essentially captives of – large systems that they cannot control – a corporation, a State, transportation networks, the technosphere as a whole. This state of human affairs is not meant as a metaphor or analogy, but as a physical necessity, a reality. We understand intuitively that we must often respect seemingly impersonal rules imposed by faceless entities, but may resist the conclusion that this condition is not curable and that it is the necessary status of most small parts of large systems. Addressing the question of how size affects the interaction between systems and between systems and their parts, the topic of the following section, makes it possible to explicitly state some of these rules, which are based on requirements of scale and organization.

Coarse graining

The adoption of a particular level of resolution or scale in describing the components of a system is called *coarse graining* (e.g. Gell-Mann, 1995). Thus, in analysing transportation systems, which play a key role in the technological processes that help define the Anthropocene (Haff, 2010, 2012), we have a choice of different levels of description depending on what question is being asked. For example, the description of traffic in terms of all the manufactured components that make up each vehicle down to the bolts that hold the wheels on, and the description of traffic in terms of density of cars on the road, represent two different levels of coarse-graining the highway-and-traffic system. The description of traffic in terms of individual cars on the highway is an intermediate level of coarse graining. At this level the details of each automobile are abstracted away, whereas in the density description of traffic only the collective effect of individual automobiles remains. The selection of a coarse-graining scale specifies the components that we can use to describe the system, allowing some and hiding others. If we are interested in timing of stop lights to minimize stop-and-go traffic we might coarse grain at the level of individual cars and ignore the smaller details of each automobile. If we are investigating regional traffic flow on major expressways we might choose a density description, ignoring the discrete nature of each automobile. We are guaranteed that there exists a coarse-grained description that will have a correspondence to the real world at the chosen scale, even though it discards much information about smaller scales, because real-world behavior at the coarse-grained scale is what suggests the coarse-grained description in the first place.

Humans and the technosphere: Six rules

In order to place ourselves, and other systems of interest, in perspective as components of the technosphere, we imagine the world to be coarse grained at the scale of a system S, which might, for example, be a human. In the three-stratum picture, similar to a concept sometimes employed in analysing the structure of biological systems (e.g. Salthe, 1985), the environment of a system S is divided into three levels or strata, Stratum I, II and III, relative to that system. Stratum II is occupied by S as well as by all other components of the environment that are resolved at the scale of S, i.e. that have a similar size. If S represents a person, then other people also occupy his Stratum II. Whatever their actual size, components that are spatially much smaller than S, such as blood cell or a transistor, occupy Stratum I (relative to S), and similarly all components, whatever their actual size, that are much larger than S, such as an office building, a city or an ocean, occupy his Stratum III. It is essential to bear in mind in the subsequent sections that, whatever the size of system S, the three strata are defined relative to that system. Using the three-strata parsing scheme, six rules are developed that govern the relation between different systems or between a system and its parts. These rules apply to humans considered as parts of the technosphere and help inform us about our place in that system, and thus in the Anthropocene.

The rule of inaccessibility

Our own Stratum I incorporates small components of our environment that normally we do not have to think about in daily life, such as a nematode or soil grain. Stratum I also includes many small technological parts, such as transistors and synthetic nanoparticles. Stratum I contains those components that are blurred away when the environment is coarse grained at our own scale. Individual transistors in a laptop might as well be atoms as far as accessibility by the user is concerned. We cannot interact with most Stratum I components directly. This is the rule of inaccessibility. The rule of inaccessibility applies in a similar way to the technosphere with respect to its Stratum I parts, such as individual humans, whom it is not able to affect directly.

One explanation for the rule of inaccessibility is that a significant difference in size between two systems implies that the larger system cannot directly influence the smaller system without also affecting many other small systems or parts that are nearby. If your hand tries to grasp a single cell in a leaf lying on the ground, the whole leaf ends up in your hand instead. The collection of affected Stratum I parts, the leaf, is in effect a Stratum II system relative to the probing system, your hand, so what began as an intended direct Stratum II effect on a Stratum I system ends up as a Stratum II effect on another Stratum II system

The rule of inaccessibility does not mean that we cannot affect a specific system or part that resides in our Stratum I, but only that we cannot do so directly in terms of variables defined in Stratum II. Two systems in each other's Stratum II can potentially interact with one another directly because their dynamics are based on the same coarse-graining scale that resolves their stratum. Indirect access to Stratum I is possible because the Stratum II levels for two systems, each of which resides in the other's Stratum II, are generally not congruent, but overlap. Overlap or fuzziness of stratum boundaries is essential for function in a world of many scales because it allows indirect communication between parts whose respective Stratum II layers do not overlap. For example, a transistor inside a computer lies deep within our Stratum I layer, where it is not directly accessible by us or by other systems in our Stratum II. To manipulate a given transistor mechanically requires the intermediary of another system or set of systems, for example a microscope equipped with a manipulator arm. The microscope and the human end of the manipulator are systems in our Stratum II. The series of linkages that transmit a human reaching motion to arm to hand to finger motion (a cascade that accomplishes hand-off of scales via overlapping strata within a single organism), and then on to the microscopic motion of a probe at the other end of the manipulator arm, work by sequential interactions between one system in its own Stratum II with a smaller system whose Stratum II overlaps that of the first.

When the chain of connections mediated by overlapping strata is clear, it may be convenient to attribute direct agency to the large system rather than to articulate in detail the chain of causation. For example, rather than running through the sequence of events from brain to grasping action, we simply say that 'he' picked up the leaf. We similarly understand that cancellation of an insurance policy has a higher source than the letter announcing the cancellation. Nonetheless, from our perspective as Stratum I parts of the technosphere, the rule of inaccessibility distorts our perception of the Anthropocene. According to the rule, the effects of large-scale technology are transmitted to us indirectly through a hand-off of scales, finally resolving into technospheric agents such as cell phones, salesmen, police, utility bills and so on, each of which lies within our Stratum II layer. The consequence for humans is that the clarity and immediacy of our experience with these Stratum II parts, with which we interact directly, tend to overshadow the importance of the more diffuse and harder-to-visualize Stratum III technosphere (see Tversky and Kahneman, 1974, for a discussion of the related phenomenon of *availability bias*). The popular concept of technology is reminiscent of the way biology was viewed prior to the conceptualization by Vernadsky ([1926] 1997) of the biosphere, i.e. that it was mainly an organismal phenomenon. For humans, the upshot of the rule of inaccessibility is to draw attention toward what we are familiar with and thus towards local cause and effect, and away from one of the principal paradigms of the Anthropocene world, namely that humans are components of a larger sphere they did not design, do not understand, do not control and from which they cannot escape.

The rule of impotence

Stratum II systems are generally unresponsive to the behavior of most of their Stratum I parts by virtue of constraints applied to enforce organization of the parts. This is the rule of impotence. If the behavior of Stratum II systems were sensitive to the individual behaviors of most Stratum I parts, then a Stratum II system would be continually buffeted by large, essentially random, forces, and would lose its ability to behave coherently and to fulfill its function. This is the physical reason that a bureaucracy does not often change a policy because of the complaint of an individual, or a highway is not usually shut down, except briefly, as a consequence of an accident. Large companies, armies, tax collection agencies and other bureaucracies seem indifferent to or uncaring about a typical individual human because such indifference is a requirement of their own continued function.

There are some exceptions to the rule of impotence. Thus, every system of many parts is a network, in the sense that there is always a set of links, however indirect, between any two of its parts. In a tightly coupled system (Perrow, 1999), a failure of a small part can under certain circumstance generate a cascade along the network, causing large-scale failure. For example, in 2003 power lines in the US state of Ohio sagged into a tree causing a power blackout across northeastern USA and southeastern Canada that affected 50 million people (Minkel, 2008). Such failures must be infrequent compared with system cycle times if the system is to persist. By contrast, in some systems a few select parts can generate a sequence of events that propagates through the network to aid system function. These parts, for example a building thermostat, can be called leader-parts or, if they are humans, simply leaders. The role of leaders is discussed in the following section. Most small parts of large systems, however, including human parts of the technosphere and its large components, are subject to the rule of impotence. The rule of impotence helps enable a key phenomenon of the Anthropocene, the appearance of large technological systems that tend to resist human objections to or interference with their function.

Leadership and the rule of control

The rule of impotence does not gainsay that certain atypical humans may significantly influence a host Stratum III system. Similar to the way in which Stratum II influence may be projected downward to Stratum I scales, the overlapping of strata provides a path by which the action of some Stratum II parts can be projected upward to the Stratum III level above. Leaders can have large effects at the Stratum III level, and for many large systems leadership is essential to system survival. A company, army or country would not last long in the absence of decisions by leaders.

Although it is sometimes convenient to view a leader as someone who causes the system he leads to behave in a manner that he himself determines, i.e. to control the system, from the point of view of the Stratum III system the function of a CEO, a naval captain or any successful leader is to more effectively enable the system to do what it needs to do to maintain viability – to be able to navigate the complex terrain of the environment within which it operates, to react to competition, to secure resources required for its metabolism and to evade or counter threats to its existence. These proclivities are by necessity built into any large-enough dynamic system if it is to survive. Leadership is one mechanism used by the system to help satisfy its survival requirements.

Leadership is possible only when the system to be led has certain simplicities that a human leader can comprehend and make use of – for example an organizational structure that is accessible through a chain of command (the embodiment of a series of overlapping Stratum II levels). The technosphere in general does not offer such simplified structure. Thus, a large naval vessel sailing alone across the sea under the watchful eye of a captain might seem a representative microcosm of a planetary technosphere sailing alone through space under the guidance of a world leader ready to take corrective actions against external threats or internal malfunction. However, there can be no such leader. The technosphere is not a giant version of a navy ship. The latter is purposefully designed according to engineering specifications to suppress as many undesirable degrees of freedom as humans can think of, and in the process to provide the captain with specified lines of control. A central purpose of the ship design process, beyond providing for suitable military capabilities, is to simplify the complexity of the machine by providing an interface so that its *apparent* or *interface complexity* does not exceed that of the captain. This is a requirement that follows from the so-called Law of Requisite Variety (Ashby, 1957; Fransoo and Wiers, 2006; Luhmann, 2012), here renamed, for clarity, the rule of control.

According to systems theory, if a system is potentially subject to N disturbances or challenges to its function and if it possesses M ways of responding effectively to those disturbances, then to regulate or control the state of the system, that is, to ensure desired functionality, M must equal or exceed N. Roughly speaking, a controller (e.g. the captain) has to be complex enough to mimic (react to) the behavior of the system that is to be controlled (the ship), a condition that can be achieved in designed systems by simplifying the system sufficiently to match the capabilities of the controller. However, the technosphere is not an engineered or designed system and during its emergence has not relied on nor required an overall leader, and in consequence lacks the infrastructure needed to support leadership. In this regard the technosphere resembles the biosphere – complex and leaderless.

Finally, if a leader of a system with built-in leadership infrastructure, such as the CEO of a corporation (e.g. Steve Jobs) or the president of a country (e.g. Xi Jinping), or an engineer or a scientist (e.g. Isambard Kingdom Brunel or John Bardeen, the products of whose genius are directly appropriated by governments or corporations), is termed a cooperative leader (i.e. supportive of the function of the system), there remains the category of uncooperative, or adversarial, leader, who opposes and is able to significantly influence one or more key elements of system function (e.g. Nelson Mandela or Mahatma Gandhi in effecting major social change).

The effectiveness of an adversarial leader, who is a malfunctioning part as far as the system is concerned, is made possible by the same kind of cascading network effects that underlie the potential failure of strongly coupled systems such as the power-grid. Strong-coupling between a large number of parts in a large system cannot be created directly or on demand by a prospective leader, but it may emerge as a system-wide (i.e. Stratum III) response to a Stratum III scale force (such as widespread political repression). The emergence of strong-coupling stimulated (say) by Stratum III level stresses due to climate change might represent a first step in the appearance of self-limiting ('thermostatic') behavior in the technosphere.

The rule of reciprocity

The rules of inaccessibility and impotence have been discussed separately to clarify the relation between a Stratum II system and much smaller or much bigger systems. These rules together with the fact that two Stratum II systems may affect one another directly imply a single rule of reciprocity that limits direct mutual interactions between two systems to those and only those that have reciprocal membership in each other's Stratum II layer. Reciprocal membership means that if one system is in the Stratum II layer of a second system, then the second system is in the Stratum II layer of the first. This relation also follows from the nature of coarse graining. The rule of reciprocity re-emphasizes the point made above, that the physical restriction imposed on humans that they can deal directly only with other Stratum II systems, many of which such as automobiles or cell phones are products of human design, encourage the anthropocentric misconception that we created and control large-scale technology.

The rule of performance

According to the rule of performance, at least some of the actions of most system parts must support the function of the system to which they belong. We recall the function of the technosphere – to extract high quality energy from the environment and to do work with that energy to sustain its own existence and that of its parts, including humans. If too many parts failed the rule of performance, then the technosphere could not function according to its description. The effect of the rule of performance is that most humans must support this functionality, for example by holding a job, reproducing, being sufficiently sociable to help sustain a human network of knowledge and cooperation, paying taxes and supporting activities such as education, without which efforts the technosphere would eventually collapse.

There are penalties for flouting the rule of performance. With regard to the technosphere, humans are not voluntary members of a system whose goods and services they use for convenience and from which they could resign if they 'wanted to'. Technology provides not just luxuries such as bath powder and steak knives, but essentials of life such as food and water, which, for the billions of humans alive today, are available only as a consequence of the function of the technosphere (e.g. fertilizers, mechanized farm equipment, efficient long-distance transportation, pesticides, medicines and so on). The technosphere locks humans into service not only by giving them what they need and want, but by the implicit threat to withdraw perquisites or even necessities of life for those who leave. A few individuals may occasionally withdraw from the technosphere voluntarily to become hermits, or fail to work in its support because of mental or physical incapacity, e.g. the sick and the homeless. From the point of view of the technosphere the latter are broken parts, and are in effect discarded from the system unless they can be repaired, i.e. made serviceable again. Humans remaining on the outside often suffer accelerated ageing

(Hahn et al., 2006), the same fate that faces other kinds of technospheric parts discarded because they no longer 'work', such as the once shiny automobiles rusting in a junkyard. The rest of us perform support tasks for the technosphere not because we know about the rule of performance, but because of incentives or constraints that lead us to participate or because of punishments that come to bear when we stray from regular performance of our tasks. Most of the time, most of us work to support the technosphere whether we know that it exists or not, and whether we want to or not.

The rule of provision

It is necessary that the parts of a system experience an environment that makes it possible for them to perform their support function. The host system contributes to maintenance of a suitable environment for its parts according to the rule of provision. A railway car is able to move easily from origin to destination because the tracks are smooth and well secured and the wheel bearings are maintained in a well-lubricated condition. The railroad system, which lies in the car's Stratum III, must provide these and other support services for its rolling stock and other components in order to be able to function itself. For its human parts the technosphere provides essential support in many different ways, for example by supplying food and fresh water to population centers, medicines to keep us healthy, the tools, systems and knowledge we need to do our jobs, and the time and recompense needed for us to be effective consumers.

The type and rate of provision are responsive to human needs and desires, the latter of which, in their acquisitive form, have no known upper bound. A consequence is that the rules of provision and performance together create conditions conducive to positive feedback. The provision of gadgets, services and systems that people want, or discover that they want, can enable or encourage new modes of human performance that support further production of these and other desiderata. In this way technology creates its own niches and subsequently expands into them, as, for example, in the recent emergence of a pervasive app market (e.g. Abowd et al., 2005) in the wake of expanding adoption of smart phones.

The stability of these growth conditions is not, however, guaranteed. Environmental degradation, global warming, a world population that continues to rise and many other developments that are driven by a high-metabolism technology, raise the question of whether the technosphere may eventually fail the rule of provision, on which civilization and its own existence depend. The rules of provision and performance, even if adhered to, do not guarantee indefinite longevity for the technosphere. The rules are only minimal requirements that must be met if a metabolizing system is to endure through many internal cycle times. A system's environment poses external challenges, some of which are generic, and point to an additional set of rules that must be followed for a system to survive long enough to overcome the challenge. Perhaps the most fundamental of these is a consequence of the second law of thermodynamics – namely, that an enduring system must eventually begin to recycle whatever fraction of its mass waste products is not recycled by other environmental systems. In the case of the technosphere, these 'other systems' are those that embody the shrinking resource called natural capital (Daily, 1997) (e.g. undisturbed soils, which can function as a carbon sink). The question of recycling and other issues pertaining to the dynamics of the technosphere that are not treated here are discussed in Haff (2010, 2012, 2013, 2014).

We note that, although the above discussion outlines six rules, logically they reduce to only four, since the rule of reciprocity implies the rules of inaccessibility and impotence. However, because our approach is physical rather than axiomatic, it is more appropriate to view the rule of reciprocity, which is not derived here from first principles, as a deduction from the rules of inaccessibility and impotence, which are physically based. The listed rules are thus not all independent, but, because each is informative, we refer here to all six rules.

Summary

The Anthropocene is a product of human activities and of technology. Creation of technology is usually considered to be a consequence of those activities and therefore a derivative phenomenon. From a large-scale perspective a different picture emerges of the relation of humans to technology, that humans are parts of a dynamic and uncontrollable Earth system from which they cannot escape and in whose service they labor. The vision of Man as a cog in a wheel, subject to a dominating and impersonal technology, has long been a trope in popular culture (e.g. the film *Modern Times*: Chaplin, 1936). The main point of the present argument is to go beyond the use of metaphor (except where it clarifies ideas) and to show from a physical point of view how certain conditions deriving from requirements of scale and organization reinforce the idea of humans as parts of, rather than simply creators and users of, modern technology.

We have outlined a set of basic dynamical rules that apply to human interactions with the technological world of the Anthropocene – the rules of inaccessibility, impotence, control, reciprocity, performance and provision. Tracing out possible consequences for human wellbeing of our asymmetrical relation to the technosphere, as described by these rules, lies substantially beyond the scope of this work. However, whether or not these rules can in themselves answer questions we have about technology and the human future, the hope is they may suggest new questions that would not be asked from a worldview in which technology was seen as simply a product of human ingenuity.

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