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Infrastructuring as a Planetary Phenomenon: Timescale Separation and Causal Closure in More-Than-Human Systems

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Abstract: *»Infrastructuring als planetarisches Phänomen: Zeitskalentrennung und kausale Schließung in mehr-als-menschlichen Systemen«.* Building on recent work identifying how the infrastructures of human social and economic life themselves depend on the "natural infrastructure" of biogeochemical systems, I explore the idea that infrastructuring – involving causal relations between subsystems operating at different timescales – might be a strategy widely adopted by matter undergoing self-organization under planetary conditions. I analyze the concept of infrastructure as it is used to describe features of the human "technosphere" and identify the importance of a difference in timescales between supporting and supported structures and processes. I explore some examples of how the wider planet might be said to engage in timescale-distancing and infrastructuring, focusing in particular on examples from the hydrosphere and biosphere. I then turn to the question of how to *explain* infrastructuring, developing a neocybernetic account of infrastructuring as involving the separation of a system into subsystems at different timescales in mutual but asymmetrical causal relations. I conclude by exploring the implications of this approach for the way we think about planets in general and the human technosphere.

Keywords: Infrastructure, infrastructuring, timescales, neocybernetics, second-order cybernetics, closure to efficient causation, autopoiesis, planetary social thought.

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1. Introduction: Infrastructure beyond Anthropocentrism

In the last few decades, the concept of infrastructure has been greatly enriched and complexified by work in the humanities and social sciences. The increased favoring of the verb "infrastructuring" over the noun "infrastructure" signifies an emphasis on the way that the backgrounded, invisible, taken-for-granted character of infrastructure, rather than being an inherent feature, is the result of a specific arrangement of social practices, and can break down, especially at moments of disruption. Susan Leigh Star and Geoffrey Bowker (2006) argued that infrastructures are complex, shifting sets of material and immaterial processes involving not only material structures but also learned practices, conventions, and standards.[1]

Some scholars have also sought to broaden discussion of infrastructure beyond humans and their technologies. As Jensen (2015, 4) summarizes the implications of this kind of work, "infrastructures are not necessarily either quite natural or quite social." For example, Maan Barua (2021) describes how anthropogenic infrastructure such as roads and railways also produces diverse mobilities and immobilities among non-human living things. Researchers such as Ashley Carse (2012), Casper Bruun Jensen and Atsuro Morita (2020), and Rosengren (2022, in this issue). explore how infrastructure projects such as the Panama Canal and the irrigation and anti-flooding infrastructures of the Chao Phraya delta in Thailand enroll natural systems into their operation. Jedediah Purdy (2021) describes more broadly how human wellbeing depends not only on the artificial infrastructure of buildings, roads, and railways, and the immaterial infrastructure of social organization, but also on the natural infrastructure of biogeochemical systems and cycles. Andrew Barry (2017, 187) similarly argues that the human infrastructure that subtends human social life is itself subtended by the natural infrastructures of "the earth, its rocks, soil and water," in his case emphasizing the way that the ultimately uncontrollable unruliness of the latter constitutes a "source of instability" for human infrastructures.

However, the extension of the concept of infrastructure in this literature still typically foregrounds humans or their works, assuming that infrastructuring always involves humans' craft, knowledge, skill, representations, and social structures, and supports human activities.[2] Star's early, classic paper "The Ethnography of Infrastructure" (1999) itself took a social constructionist position, suggesting that whether or not something is an infrastructure is not an objective matter, independent of its perception as infrastructure, but

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[1] On standards, see also Busch (2011).

[2] Although Puig de la Bellacasa (2014, 32) discusses soil as "the 'infrastructure' of our living ecologies on Earth."

always relative to specific social practices. In many ways, the critical human geography, sociology, and anthropology of infrastructures could be said to have continued or even intensified the anthropocentrism of the non-social scientific understanding of infrastructure. In this paper I want to take a rather different approach, seeing what happens if we view infrastructure through the lens of what Nigel Clark and I (2021) call "planetary social thought": a way of thinking about social phenomena that – while conserving the critical dimension of social science – situates them firmly within the story of a planet that is evolving and organizing itself over deep time.

2. Infrastructure, Definitions, and Temporality

The word "infrastructure" appeared in French in the 19th century, but after World War II became widely adopted in the English language in the Cold-War military context of building "fixed military facilities." NATO, for example, defined infrastructure variously as "static buildings and permanent installations required to support military forces," or "the static items of capital expenditure which are required to provide the material support for operational plans necessary to enable the higher command to function and the various forces to operate with efficiency" (NATO Infrastructure Committee 2001, 19).

From that point on, "infrastructure" became a widely adopted term in the English-speaking world, spreading out from its initial military context. Carse (2017) has usefully summarized the shifting meaning and use of the term and its gradual widespread adoption. The numerous published definitions of infrastructure are useful for teasing out the different elements and dimensions that have been brought together in the contemporary concept. Many such definitions are *ostensive* definitions, which simply list familiar examples such as buildings, transport, and communication systems and power supply networks.[3] Nevertheless, it is not hard to find *analytical* definitions of infrastructure, such as the early NATO ones above, which instead try to define it from first principles – and these are particularly revealing.[4]

The following (containing within itself an instance of an ostensive definition, that I have here placed within square brackets), is a good example of an analytical definition:

> The infrastructure of a country, society, or organization consists of the basic facilities [such as transport, communications, power supplies, and buildings,] which enable it to function.[5]

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[3] These lists, of course, can themselves be revealing.

[4] On definitions of infrastructure, see also Edwards (2003, 186-7).

[5] https://www.collinsdictionary.com/dictionary/english/infrastructure (Accessed November 15, 2022).

We can break down this and other analytical definitions into five typical "elements," that I will collectively treat as constituting an initial, working definition of infrastructure. The first two elements correspond loosely to the two parts of the word: "infra-" and "-structure"; the final three go beyond the word itself to name what is implicitly understood in any use of the word: that infrastructure points beyond itself and has a function, purpose, or telos.[6]

a) BASENESS. Corresponding to the prefix "infra-," meaning "below," but with a secondary meaning of "within" (Oxford English Dictionary 2022), definitions have one or more adjectives that invoke ideas, perhaps, of lower status or value – but also of chronological and ontological priority or necessity, such as "basic," "foundational," or, as in the NATO definitions, "static."
b) DISTRIBUTION. This element in definitions, corresponding to the "-structure" in "infrastructure," draws attention to the distributed, multi-sited, patterned nature of infrastructural provisioning, manifest in such nouns and noun phrases as "services," "system," "framework," "network," "skeleton," "public works," or "architecture."
c) SUBTENDING. Definitions typically have a finite verb, such as "enable," "support," "serve," or "help," that indicates an asymmetrical relation with a distinct set of processes or activities.
d) TARGET. Definitions have another noun specifying the object or target of that verb, such as "society," "community," "nation," "economy," "organization," or "activity."
e) GOAL. Last, definitions typically have an infinitive verb that specifies more precisely the goal or function of the infrastructure in terms of what aspect of the target is being helped or supported – for example, "to function," "to run smoothly," "to continue," "to grow," or "to meet needs."

The results of this exercise resonate, to a large extent, with much of the social science literature on the topic – for example, with Star's (1999) argument that infrastructure is typically invisible, backgrounded, taken-for-granted, "ready-to hand" (1999, 380), and that infrastructure is an inherently relational and ecological concept. However, whereas the emphasis in the social science literature is, understandably, on the role of social practices and acts of representation in stabilizing ideas of infrastructure, I want to push back on this. Inspired partly by Elizabeth Grosz's concept of "geopower" (Grosz, Yusoff, and Clark 2017) – which she uses to argue that all human collective agency is ultimately subtended and conditioned by the forces of the non-human world – I want to explore the idea that infrastructure has its own physical dynamic

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[6] In this paper I am deliberately stretching the language of teleology and purpose beyond the realm of human consciousness and even biological life. The debates about such a move, and about the distinction between teleology and teleonomy, are complex and contested and there is not space to go into them here.

that exceeds not just human control but also human acts of representation. Later on in the paper I will argue that it is the distinctive "causal architecture" of a system or subsystem that enables it to meet the definition of an infrastructure as I have unpacked it above. But first I want to draw attention to the importance of different timescales in infrastructure.

There has been some discussion of temporality in the existing literature on infrastructure. Star and Ruhleder (1996, 112-3) posed the provocative question "when is an infrastructure?" answering in resolutely social terms: "Within a given cultural context," they write, "the cook considers the water system a piece of working infrastructure integral to making dinner; for the city planner, it becomes a variable in a complex equation." But there are other temporal aspects to infrastructure in which the inner logic of its physical organization becomes harder to ignore. Carse (2017, 29) points out that denoting something as "infrastructure" is partly a matter of organization and planning, demarcating that which has to be constructed not just *beneath* but also *before* the superstructure that depends upon it. But he also relates the spread of the term "infrastructure" to the emergence of French structuralist theory in the 1960s, with its idea that "the phenomenal world could be analyzed in terms of *deep* and abiding structures" (ibid., 35) – and it is this idea of infrastructure as slower, as functioning on a longer timescale, that I want to investigate further. The term I will use to refer to this temporal feature of infrastructuring is *timescale separation*: a difference in the characteristic temporal scale between an infrastructure and the devices and activities whose operation it supports.

There has been some scattered but highly suggestive discussion of timescale separation in the infrastructure literature. Paul Edwards (2003, 194-5), for example, highlights the way that modern infrastructure works at the historical timescale of decades and centuries, and suggests that it functions to mediate between the geophysical time of millennia and longer on the one hand, and the human, animal time of hours, days, and years on the other, in the attempt to create an ordered and predictable artificial nature for modern societies. Other work has identified the importance of timescale distancing *within* the human "technosphere" (Haff 2014c) – between its different "subcompartments." Zmarak Shalizi and Franck Lecocq (2009), in their work for the World Bank, itself based on Jaccard and Rivers (2007), argue that capital stock can be disaggregated into subgroups with different characteristic lifespans: their Group 1 consists of consumer durables (5 to 15 years); Group 2, factories and power plants (15 to 40 years); Group 3, road, rail, and power distribution networks (40 to 75+ years); and Group 4, land use and urban form (a century or more). It is notable that, whereas it is Group 3 that is conventionally classified as infrastructure, it could be argued that *all* groups play infrastructural roles to others on shorter timescales.

The same sort of timescale separation in human artefacts can also be seen at smaller spatial and mereological scales. Building on the thought of architect Frank Duffy and Alex Henney (1989), Stewart Brand (1994) writes about the "shearing layers" of a building: sets of components that metaphorically "slide across" each other at different timescales. Brand identifies six such layers that he calls "site" (centuries), "structure" (30-300 years, with a mode around 60 years), "skin" (exterior surfaces, 20 years), "services" (working systems, 7-15 years), "space plan" (3-30 years), and "stuff" (days to months). Once again, a decomposition of the technosphere based on timescales is revealing, suggesting that infrastructuring, as a relational phenomenon, is not confined to one "layer" or "stratum," but is distributed across many.

Can the concept of timescale distancing help us to understand infrastructuring as a more-than-human phenomenon: as one that has played a role in the wider story of the Earth? Why does infrastructuring involve timescale distancing, anyway? Before exploring such questions, let us briefly consider, on the basis of the discussion of the concept of infrastructure so far, what it might mean to look for patterns of infrastructuring within planetary systems.

The above analysis would suggest a number of criteria for identifying instances of infrastructuring beyond the human-made world. First, we would be looking for two or more processes that are, to some extent, independent and separable. Second, this independence would involve them operating at different timescales – some faster, some slower – and possibly a *multimodal* distribution of timescales, suggesting a number of "layers" with their own different characteristic distributions of timescales.[7] Third, we would look for asymmetrical relations of dependence between these timescale-distanced processes, in that they would affect each other in different ways. Fourth, this asymmetrical relation should be able to be described in some sense as a functionality or an enabling in relation to a phenomenon that can plausibly be said to go better or worse – as broadly "teleological." In the next section, armed with such ideas, we will explore some candidates for examples of timescale separation *within* planetary processes and ask whether we can see them as involving a kind of planetary infrastructuring.

3. Infrastructures of the Earth

Earth processes certainly span a vast range of timescales – from atmospheric turbulence (minutes and hours), volcanoes and weather systems (days), and seasons (months) to glaciations (thousands of years) and mountain building

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[7] "Multimodal" in this sense means having more than one maximum in its probability density function – for example, a graph where "x" is timescale and "y" is the number of entities or processes with that timescale, with several different peaks, suggesting clusters of entities with similar timescales.

and plate tectonics (millions of years) (National Research Council 1988, 27). But what – if any – role does this timescale distancing play in the ongoing story of the Earth? In the rest of this section, I will briefly explore this question in relation to two specific areas – the hydrosphere and the biosphere. In both cases, I will suggest that, while not all manifestations of timescale distancing in Earth processes are necessarily evidence for processes of planetary infrastructuring, as defined above, some are suggestive that such processes are indeed taking place. The process of teasing out this distinction can help us to get clearer about what kind of theoretical approach will help us recognize and understand more-than-human, planetary infrastructuring.

Given the role that water plays in living processes, the Earth's hydrosphere – the sum of liquid water on the Earth and its movement and transformations – can, in many ways, be seen as a vast infrastructure to the biosphere. However, processes *within* the hydrosphere – especially those involving its interactions with the atmosphere and lithosphere – seem to cover the full range of timescales in Earth processes, suggesting that there might be other infrastructuring processes involving the hydrosphere. Looking at river development alone, Jef Vandenberghe (1995, 637) distinguishes a number of timescales – 100,000s of years (glacial/interglacial sequences); 10,000s of years (cold-warm cycles); 1,000s of years (intrinsic evolution); and 100s of years (lower order climatic change). However, Vandenberghe's focus is on the forces that determine changes at those timescales, rather than any effects that this timescale-distancing might have. Other work on rivers and timescales, such as that by Donovan and Belmont (2019), focuses on the need to observe rivers at appropriate timescales to record specific phenomena, without making any claims about possible causal roles being played by such timescale distancing.

For the hydrosphere to be said to be engaging in infrastructuring in the sense we have defined it above, we would want to see some kind of self-organization, with timescale-distanced processes affecting each other in complex ways. And certainly, looked at broadly, the Earth's hydrosphere appears to be not a simple continuous, hydrostatically equilibrated stratum of liquid, but an active, materially closed system held far from gravitational, thermal, and chemical equilibrium (Shiklomanov 1993; Shvartsev 2009). The Earth's hydrosphere, in its self-optimizing cycling – returning over a third of the precipitation falling on the land to the ocean, in an average of 16 days (Shiklomanov 1993, 15) – also seems to exhibit the "self-organized criticality" whereby complex systems maintain themselves in a system state that allows them to self-organize (Bak 1996). Anticipating the neocybernetic language introduced later, the Earth's materially closed hydrosphere might be said to exhibit "self-referentiality," a key feature of the "autopoiesis," or self-making, that is said to be characteristic of biological life (Maturana and Varela 1980). While obeying the laws of physics, the hydrosphere generates its own distinctive processes such as erosion, deposition, and meandering, that seem to require us to adopt a distinctive vocabulary and language if we are to describe them – processes that can be said to be *perturbed*, rather than simply causally affected, by changing conditions outside the hydrosphere.

At a smaller scale, individual rivers seem to exploit timescale-distancing between their component processes to generate infrastructuring effects. Through processes such as erosion, solution, deposition, and bed-armouring, they organize their interactions with the lithosphere to create a more ordered environment for flowing water (Rinaldo et al. 1993; Leeder 2011, 246-7). As a river flows over long periods across the subaerial land surface, interactions between the fast processes of river flow and slower processes of landform change allow it to carve the solid interface to create a bed to channel and speed the flow and create complex fractal networks that drain in optimal ways (Rodríguez-Iturbe and Rinaldo 1997). The ability of a river system to order and simplify its own lithic milieu through this interaction across timescales seems related to its possession of distinctively hydrological processes. At a much shorter timescale, a river will also configure its flow internally, creating enduring layers and eddies within the edge of the moving body of fluid that serve to reduce the friction experienced by the main flow of the water, and to increase the overall flow. This could be said to be infrastructuring in the internal sense of "infra-," in which the subtending structure is *inside* the subtended process, like a skeleton.

Now we turn to life – and it is perhaps in biology and specifically *evolutionary* biology that the separation of timescales is most likely not to be just accidental or incidental, but an essential feature of the overall phenomenon. Since August Weismann's postulation at the end of the 19th century of an inherited "germ plasm," fundamentally distinct from the somatic cells of individual organisms, life in general has come to be seen, in effect, as a slow infrastructure on which living organisms play out their fast, evanescent dramas (Ansell Pearson 1999, 5-6). Thus, Arnaud Pocheville (2019) argued that the classical Darwinian separation between the ontogenesis of the individual organism and the evolution of genes is fundamentally a separation of timescales: from the point of view of genes and evolution, organisms and their physiology and behavior are instantaneous, and from the point of view of organisms, genes are static. Tim Lenton and colleagues (2018, 639) similarly distinguished fast ecological processes from slow evolutionary ones.[8] The overall sense here is that the separation of timescales in biological phenomena – between the long timescales of macroevolution and the more familiar timescales of individual organisms, but also between the latter and the timescales

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[8] Of course, newer ideas like niche construction and evolutionary developmental biology complicate that timescale separation in interesting ways by saying that evolution can occur on the timescale of an individual. According to such "extended evolutionary" ideas, processes at different timescales become entangled in hugely complex ways (see Pocheville 2019).

of much faster, intracellular processes – is an important part of the very machinery of life on Earth.

4. Explaining Infrastructuring

Why is it that dynamic systems in both the human, technological realm and the wider more-than-human world seem inclined to separate into processes at different timescales? And under what conditions does this timescale distancing become full-blown infrastructuring, as we have been defining it? The examples considered in the last two sections seem to range between cases in which timescale distancing might be nothing more than an epiphenomenon – a side-effect of the way that different elements of a system just happen to operate at different characteristic speeds – and cases in which timescale distancing does seem to be playing a crucial role in the self-ordering of a complex system. In this section I consider four different ways of explaining timescale separation and infrastructuring in both the human-built technosphere and the wider more-than human world. While all four approaches might be useful to explain some forms of timescale-distancing, it is the final, neocybernetic approach that I want to suggest is crucial for understanding when timescale distancing becomes infrastructuring proper.[9]

First, then, it is important to acknowledge that some timescale distancing might not be evidence of fully fledged infrastructuring, instead, simply being an accidental feature that does not play a significant causal role. In this case, timescale distancing could be explained reductionistically, as the result of what Terrence Deacon (2012) calls "homeodynamics," in which global properties are produced bottom-up from the interaction of the individual parts as they seek thermodynamic equilibrium. For example, the separation of the Earth into different compartments with different physical properties and characteristic timescales is, to a large extent, the result of the very gravitational processes through which planets form, as the diverse chemical elements making up the nascent planetary body find their "hydrostatic" level in the forming spherical body of the planet and adopt different phase states (solid, liquid, gas) and mineral types according to the ambient temperature and pressure of that part of the planet (DeLanda 1992, 140-3; Clark and Szerszynski 2021, 79-80). The different characteristic timescales of processes internal to these regions might then simply be the resulting properties of the different physics of the kind of matter gathered there under those specific conditions. Similarly, the multiple layers of buildings operating on separate timescales (Brand 1994) *could* be dismissed as a mere side-effect of the simple

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[9] For a similar application of competing explanations for planetary-scale life phenomena, as captured in the Gaia hypothesis, see Rubin and Crucifix (2022).

fact that different components of a building have different material properties – suggesting that Brand's language of layers merely "shearing," "sliding across," or otherwise ignoring each other might sometimes be appropriate.

Second, however, infrastructuring might arise, and be reinforced, due to the special kind of thermodynamic processes that occur in far-from-equilibrium, "dissipative" systems.[10] Dissipative systems are systems in which at least some of the energy being transformed does not do "useful work," but is dissipated: converted into heat or other kinds of disorganized energy that are thereby no longer available to do work or be converted into other forms of energy. As the chemist Ilya Prigogine (1969) observed, such processes of dissipation often seem to generate longer-lived structures within themselves that he called "dissipative structures." These structures are dissipative not just because they are *made* of dissipation (so that, if the dissipation stops, they disappear); they also seem to function to *increase* dissipation. This idea, that dissipative processes will exhibit a tendency to generate longer-lived structures, is an example of attempts to "extend" the second law of thermodynamics: to specify more closely how systems far from thermodynamic equilibrium will not just tend towards equilibrium as the second law states, but do so in interesting and often seemingly creative ways.[11] Perhaps the most well-known case of this involves the emergence of Bénard cells in a pan of heated oil: some of the convective energy flow from the hot lower regions to the cooler surface is diverted into creating an infrastructure of long-lived, overturning, hexagonal convection cells that have the overall effect of producing a faster degradation of the temperature gradient (Schneider and Kay 1994; Deacon 2012, 250-3). Thus at least *some* forms of timescale separation can occur outside the social and biological realms, but still be more than an incidental side-effect – they can be a feature of the emergence of longer-lived infrastructures that support and even optimize other, faster processes. The long-term behavior and development of the human technosphere seems at least partly amenable to analysis in such terms (Herrmann-Pillath 2013; Garrett 2014; Haff 2014b; Jarvis 2018).

Third, at least *some* forms of timescale separation might be explained in an *evolutionary* way, as resulting from the "selection out" of processes and systems that operate at particular timescales. Some forms of this selection could result from the simple fact that configurations that are stable at longer timescales, by definition, last longer. Lenton et al. (2018) speculate that such dynamics might be at play in macro-evolutionary processes, using the phrase "sequential selection" to describe the process whereby, over time, living systems are able to find a stable state because fragile configurations are short-

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[10] For thermodynamic approaches to the human technosphere, see, for example, Garrett (2014) and Jarvis et al. (2015).

[11] On the attempt to go "beyond the second law" of thermodynamics, see, for example, Dewar et al. (2014).

lived, whereas stable ones persist (2018, 633).[12] Another possibility is that – given enough time, complexity, and freedom – a system will evolve mechanisms and regulatory responses at a range of timescales in order to have the best chance of maintaining its operation over time. Supporting evidence for this general idea comes from Joe Rowland Adams and Aneta Stefanowska's research on the synchronization of networks of cyclical metabolic processes within organisms. Their work suggests that what is often taken as "noise" in living systems is actually an adaptive spread of frequencies that make the systems more resilient against perturbations at any given timescale (Rowland Adams and Stefanovska 2021, 9-10).

However, thermodynamic and evolutionary explanations might be insufficient to explain all complex-system dynamics in the interaction between Earth processes at different timescales. For example, Williamson, Bathiany, and Lenton (2016) explored the effects of timescale separation between the internal system time of Earth systems (such as the annual cycle of vegetation) and the temporality of external forcing (either fast "noise" or slower cycles such as changes in insolation). This work reveals the very different patterns of metastability and instability, bifurcations, and tipping points that occur when the timescales of forcings are either much slower than, similar to, or much faster than the internal time of a system. Such elaborate responses, I would argue, suggest that planetary infrastructuring involves complex recursive loops of causation that are difficult to describe in solely thermodynamic terms.[13] Similarly, if a system evolves mechanisms to cope with environmental perturbations at different timescales, these can be so qualitatively different that they come to be constitutive features of a radically new kind of system governed by a distinctive new evolutionary logic. For example, if the Earth's biosphere has indeed been pressed to discover ways of manifesting both "robustness to fast transient changes (homeostasis), and adaptation to sustained (directional) changes" (Lesne 2017, 64), it has thereby produced a series of "major transitions" that have involved transformations in the very units and logic of evolution on Earth (Maynard Smith and Szathmáry 1995).

Fourth, then, I want to suggest that we might need to move beyond explanations of timescale distancing and infrastructuring based on thermodynamic imperatives or on variation-and-selection processes, and embrace cybernetic and, specifically, *neocybernetic* forms of explanation. Neocybernetics, or "second-order" cybernetics, rejects the more mechanistic framing of early cybernetics based on the idea of homeostatic feedback, instead emphasizing the importance of cognition and sentience in self-organizing

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[12] Stable configurations tend to require the regulation of the environment, which, according to Lenton et al. (2018), itself seems to require the separation of fast ecological and slow evolutionary processes.

[13] Although some theorists such as Peter Atkins (1984) make impressive attempts to build theories of complexity on thermodynamic foundations.

processes (see Clarke 2020). Described variously as "the cybernetics of cybernetics" (von Foerster 1979), or as moving the focus from "observed" to "observing" systems, neocybernetic accounts of self-organizing systems sometimes focus on including the observer of the system in the analysis and, at other times, on the broader goal of including ideas of cognition and sensemaking in the description of self-organizing systems.

An influential formulation of this kind of approach was Humberto Maturana and Francisco Varela's (1980) concept of "autopoiesis" (literally, "self-production"), originally developed to capture the distinctiveness of living things. Drawing on linguistic ideas of self-referentiality, Maturana and Varela's insight was that living systems – in contrast, for example, to factories – create the components that they need and, thereby, also maintain the structure that ensures these components continue to be created. However, an arguably more fundamental feature of the distinctiveness of living systems, as formulated by neocybernetics and ideas of autopoiesis, self-reference, and recursivity is what Robert Rosen (1991), building on the work of the mathematical biologist Nicolas Rashevsky, called "closure to efficient causation." This concept is quite distinct from the question of whether a system is open or closed to flows of matter or energy: as Bruce Clarke (2020, 39) put it, "[e]ven while autopoietic systems are environmentally open to material-energetic fluxes or semiotic mediations, their operations are internally closed so that the system sequesters its integrity as a functional unity." Rosen adapted Aristotle's fourfold typology of causation – material, efficient, formal, and final causation (Aristotle 1998) – to argue that living things are more than mere mechanisms or machines (and thus cannot be simulated by finite-state machines such as modern computers) because of their complex, recursive causal architecture. Whereas machines have their efficient cause (that which brings them about) outside themselves, the recursive metabolic and repair processes within living things can be seen as generating closed loops of efficient causation. This means that, if such a system changes due to changes in its environment, this change is not simply mechanically caused by the latter: a system that is closed to efficient causation can only respond *under its own terms*, generating a response that is mediated through how the system *perceives* those environmental changes in terms of its own internal operations.

In this paper I want to see whether such ideas can usefully be extended beyond living systems to the analysis of infrastructuring dynamics in human and planetary systems.[14] In the next section I will sketch the outlines of a neocybernetic approach to timescale-distanced infrastructuring, one that analyses processes of infrastructuring as involving a complex organizational

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[14] Clarke (2020, 5) introduced the term "metabiotic" to describe non-living systems that exhibit autopoiesis, suggesting that such systems must necessarily involve interaction with living systems. I am going further in this paper, exploring whether autopoietic behavior can occur even in the absence of biological life.

architecture involving different kinds of causation in interaction across timescales.

5. The Neocybernetics of Infrastructure

Viewed through a neocybernetic lens, infrastructuring is an emergent process that involves "circular" causation. The idea of circular or recursive causation is invoked in theories of emergence as an explanation for how a system can exhibit powers and behaviors that are not possessed by its individual component parts.[15] This is generally conceived as involving the coupling of causal processes across compositional levels in which the interaction of lower-level elements produce higher level structures and order (bottom-up causation) that, in turn, affect the behavior of the lower level elements (top-down causation) and vice versa (e.g., Lesne 2013; Deacon 2006). However, I have been suggesting that *timescale separation* can also play a key role in providing sufficient insulation between material causal processes to allow forms of circular causation to arise. Infrastructuring, in its full sense, I am thus proposing, might require a system to be organized into distinct subsystems of processes occurring at different timescales, thus constituting semi-autonomous "causal domains" that are, nevertheless, bound together in some form of "circular causation."

How might one analyze a given case of infrastructure in this way, and how might the resulting analysis be guided by – but also require the revision of – our initial working definition of infrastructure in terms of "baseness," "distribution," "subtending," "target," and "goal"? I want to suggest one approach, using Rosen's Aristotelian-inspired typology of material, efficient, final, and formal causation. Analyzing infrastructuring in this way would involve identifying one or more *material causes* (substances or entities that are being moved or transformed and the physical processes of movement and transformation themselves); *efficient causes* (processes modulating the movement and transformation of the aforementioned material causes); and *final causes* (ends or purposes that the process of infrastructuring seems to be supporting).

We might start the task of distinguishing material from efficient causes by determining whether candidate causes are (at the timescale of the target activity apparently being supported or enabled) transformed or conserved: in technical terms, whether they appear to be an "asymmetry" or a "symmetry." In processes of infrastructuring, material causes would be expected to exhibit *asymmetry* (in that they proceed differently than they would have without the infrastructuring), whereas efficient causes would exhibit *symmetry* (in that, at that timescale, they are conserved: they are at least left unaltered by the

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[15] See, for example, the discussions in Clayton and Davies (2006).

process of infrastructuring and are even possibly reproduced by it) (Montévil and Mossio 2015, 184).[16]

However, identifying material, efficient, and final causes in this way is likely to require a certain amount of revision of the conventional categories that we use to describe infrastructuring processes. Some *material causes* are likely to map fairly well onto existing categories used to describe the "target" of infrastructure: collections of individual activities facilitated by infrastructures, for example, such as the journeys of vehicles or the preparation of meals. However, others will involve distributed, networked processes occurring in the infrastructure, such as flows of electrons. Identifying *efficient causes* is likely to involve even more redescription and revision of our existing language – not least involving concepts that cut across conventional categories between psychological, social, technological, and planetary processes. And identifying the *final causes* operating within a case of infrastructuring – the way that the system seems pulled towards emergent goals, or, to use a term from complexity theory, "attractors" – might require us to be open to the possibility that the system is oriented toward ends that are radically different from the purposes that are ascribed to it by human beings (Haff 2014a).

Finally, in a given example of infrastructuring, identifying all of the material and efficient causes involved, plus all the relations of entailment between them, would be to identify the *formal cause* of the infrastructuring process: that is, the overall causal architecture that enables all the constituent causes to bring about their combined infrastructuring effect. Assuming that we are looking at a genuine case of infrastructuring – in that the "work" done by the system and its organization is "propagating": self-reinforcing and self-complexifying (Kauffman 2019, 17-31) in ways that make it seem to seek out final causes – one would expect this formal-cause architecture to involve chains of efficient and material causation that close back on themselves in self-referential cycles that – while perhaps not being totally or enduringly closed to efficient causation like those of a living organism – nevertheless produce a self-perpetuating, self-organizing meshwork. In such a meshwork, there will be slow processes acting as efficient causes modulating fast processes, but there will also be ways in which fast processes loop back to act as efficient causes modulating slow processes (Montévil and Mossio 2015, 186).

6. Conclusion: Planetary Infrastructuration

In this article I have been exploring the possibility that infrastructuring might be a more-than-human, planetary phenomenon: not just that human

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[16] In this sense, efficient causes can usefully be conceived as "catalysts," which, in chemistry, are substances that change the rate of a reaction without directly entering into it or being consumed by it.

infrastructures depend on natural systems that underpin them and make them possible, but also that human-centered infrastructuring might simply be a variation on a more general phenomenon in the ongoing self-organization of planets. I analyzed the concept of infrastructure as it is usually defined, proposing a working "analytical" definition with five distinct elements, and suggested that timescale separation might be a fundamental aspect of infrastructuring. I looked at timescale separation in a range of Earth processes, especially rivers and organic evolution, identifying some instances that seem closest to our working definition of infrastructuring. Then I turned to the question of how to *explain* timescale distancing and infrastructuring in ways that would not rely on an a priori distinction between the human and the inhuman, suggesting that at least some instances require a neocybernetic understanding based on ideas of self-reference and causal closure. I then briefly sketched one idea for what a neocybernetic analysis of infrastructure might look like. I want to conclude the article by trying to spell out what I think are the main implications of this way of thinking about infrastructure.

First, I hope that my analysis convinces at least some readers that social scientists should attend more to the *physical* dimensions of infrastructure. The existing social science literature on infrastructure has understandably focused on pointing out their important semiotic and social dimensions. It is true that infrastructure can be a slippery concept, and that our conventional ways of talking about it might systematically obscure aspects of its fundamental character. However, I have tried to show that there are important resources in the study of natural phenomena that we can use to look at infrastructure in fruitful new ways: that infrastructures approached as complex physical systems exhibit patterns of self-organizing behavior that are amenable to systematic analysis.

Second, I have suggested that more research should be done on the role that *timescale separation* plays in infrastructuring. Rather than infrastructure being an (in-principle) static backdrop for the activity that it supports – and rather than, as much social science seems to imply, any timescale attributed to infrastructure being a mere social construction – there are ways of seeing infrastructure as having its own, long timescale. "Everything flows" (Nicholson and Dupré 2018); it is just that infrastructure flows more slowly – suggesting that the "infra-" prefix in infrastructure is similar to the "infra-" in infrasound, in indicating longer timescales. Furthermore, even the simple binary distinction between (slow) infrastructure and (fast) supported activity is likely to break down, on further investigation, into a far more complex pattern of multiple distributed timescales across a range of entities and processes that only loosely gather themselves into clusters of entities and processes with similar timescales and similar functional roles. This all implies the need for systematic research into timescale separation across a range of infrastructuring processes, both human and inhuman in origin.

Third, I have argued that understanding the role played by timescale separation in infrastructuring processes requires a *neocybernetic* analysis of their recursive causal architecture. This implies a possible research programme involving the formal diagramming of the relations of causal entailment in examples of infrastructuring, analogous to the entailment diagrams developed for the organic realm by pioneers of mathematical biology such as Rashevsky (1954), Rosen (1991), and Louie (2017). I have only briefly been able to sketch what this might involve: analyzing the different timescales involved in different processes and transformations; separating material causes that are altered within infrastructuring processes from the enduring efficient causes that modulate them; identifying how chains of causation can loop back in recursive cycles, making possible final causes of functionality; and building a picture of the overall architecture or organization of these causal relations across timescales as a formal cause. Viewed in this way, infrastructures are reconceived as architectures of causation in which *efficient* causation – rather than material causation, or human, social action – is the crucial category. Infrastructuring can be seen as involving causal structures that coax a system into what C. S. Peirce called a "habit" (Anderson and West 2016): a tendency to occupy a restricted portion of its otherwise much larger possibility space – and thereby make otherwise unlikely events likely, or even inevitable.

Fourth, just as Rashevsky (1954) suggested that a formal topological diagramming of living things might reveal a fundamental commonality hidden behind the apparent diversity of physical processes in living things, it might be that this formal diagramming reveals how infrastructures that appear radically different have an identical causal architecture. But, on the other hand, it might help us to identify families of infrastructures with very different causal architectures across the human and more-than-human realms.

Fifth, the *planetary* approach I have been describing further radicalizes the idea that human infrastructuring, far from disconnecting us from wider planetary processes, connects us more firmly to them. It is not just that anthropogenic technical infrastructures themselves enroll and depend on natural processes and cycles. Timescale-separated infrastructuring is a metapattern (Bateson 1979; Volk 1995): a widespread "pattern of patterns" that manifests across a diverse range of planetary contexts and material substrates. It is not just that, in gravitationally collapsed and chemically diverse planetary bodies held away from thermal equilibrium, processes with different timescales sit alongside each other, or even that such timescale-distanced processes affect each other in complex ways. It is that, in such contexts, a dense, interconnected meshwork of causation can arise that involves processes on different timescales modulating each other in ways that give rise to function and purpose.[17] Such an approach can help us explore the way that human life always opens up into the radically inhuman – that human powers are always a collaboration with the powers of other material things with their own endogenous dynamics (Clark and Szerszynski 2021).[18] It might also help prepare human thought for the unimaginably diverse forms of complex, organized matter that we may encounter on other planets, even in the absence of biological life (Szerszynski 2019).

Sixth, the idea of infrastructuration advanced here could reinforce decolonizing moves in recent social thought by providing new ways to challenge modern, European assumptions that humans can safely and justly insulate themselves from planetary forces through standardized technological systems (Clark and Szerszynski 2021, 100-22). Edwards (2003, 195) suggests that we should regard infrastructural failure not as a mere exception or accident, but as revealing something profound about how infrastructures depend on a greater, planetary infrastructuring: "infrastructures fail precisely because their developers approach nature as orderly, dependable, and separable from society and technology – an understanding that is in fact a chief characteristic of modern life-within-infrastructures." European modernity's sense of itself as exempt from natural limits has depended on the infrastructural smoothing of planetary variability – but this itself depended on the systematic exposure of racially-othered bodies to dangerous planetary forces (Clark and Szerszynski 2021, 177). Regarding infrastructure as a planetary phenomenon perhaps implies that "moderns" should learn to accept that perfect predictability is an unrealistic and counter-productive expectation. The modes of infrastructuring characteristic of Indigenous and colonized peoples – subtended on long timescales not by standardized, distributed technological systems but by transformed ecological systems (Pyne 1997) or enduring patterns of social cooperation (Simone 2004) – are only partly to be understood as a poor substitute for the "real" infrastructure of modern societies, necessitated as it has been by centuries of unequal exchange between different regions of the planet (Hornborg 2011). They might also give us clues about a more complex and realistic understanding of infrastructuring suitable for a near future in which *all* peoples of the Earth are likely to be exposed to planetary variability.

Finally, I want to close by making a modest terminological proposal. In this paper I have largely followed my social science colleagues in favoring the verb (or gerund) formulation "infrastructuring," rather than the more

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[17] Axel Kleidon's (2016, 15-7) analysis of the thermodynamics of the Earth system starts to feel rather neocybernetic, with a complex meshwork of relations across timescales, involving a cascade of energy conversions across a chain of Earth subsystems in one direction being regulated by a cascade of "effects" in the other.

[18] My references in the paper to the "human technosphere" have, therefore, been an oversimplification: a technosphere can never be fully human.

conventional noun "infrastructure." Embedding the noun "infrastructure" within the verb "infrastructuring" does usefully draw attention to the active nature of infrastructure: the latter might work at a longer timescale than the activities that it "supports," but it still a dynamic, active entity. However, my analysis above also suggests that it might be useful to go further: to situate the active dynamic of "infrastructuring" within the more encompassing abstract-noun concept of "*infrastructuration.*" An infrastructuration – as captured in a formal diagramming of an example of infrastructure, whether human or more-than-human – would include not just ongoing processes of infrastructuring, but also the whole architecture of causal entailment: the "formal cause" that makes the infrastructuring possible. A systematic investigation of such infrastructurations might help us better understand the dynamics of the human technosphere and the wider Earth, and better grasp the full range of different possible planetary – and interplanetary – futures.

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