Machines as manifestations of global systems: Steps toward a sociometabolic ontology of technology

Alf Hornborg

Human Ecology Division, Lund University, Sweden

Abstract

Anthropologists have generally found it reasonable to understand the Industrial Revolution in Britain as a product of global historical processes including colonialism and the structure of world trade. The extent to which the industrialization of British textile production was contingent on global processes has been illuminated in detail by historians such as Joseph Inikori. Andre Gunder Frank proposed that we should reconceptualize technological development as a ‘world economic process, which took place in and because of the structure of the world economy’. Yet the theoretical implications of understanding industrial technological systems as global and unevenly distributed phenomena have, by and large, not contaminated mainstream conceptions of technologies as politically neutral and fundamentally innocent manifestations of enlightenment, detachable from the societal contexts in which they have emerged. Social theory nevertheless offers perspectives for a radical rethinking of this conventional ontology of modern technology. If the premises of actor–network theory, material culture studies, Marxism and poststructuralist critiques of power and inequalities are combined with the perspectives of ecological economics on global social metabolism, the fossil-fuelled textile factories of 19th-century Britain can be reinterpreted as social instruments for appropriating embodied human labour and natural space from elsewhere in the global system. A renewed ‘anthropology of technology’ might focus on the observation that technology is not simply a matter of putting nature to work, but a strategy of putting other sectors of global society to work.¹

Corresponding author:

Alf Hornborg, Human Ecology Division, Lund University, Sölvegatan, 12, 233 62, Lund, Sweden.
Email: alf.hornborg@hek.lu.se
Keywords  
Technology, sociotechnical system, world-system, unequal exchange, social metabolism

Introduction

For decades, a central theoretical challenge for me has been how to articulate and pursue my intuition that our most tangible manifestation of capital accumulation—modern technology—is to be understood as a global phenomenon (Hornborg, 1992, 1998, 2001). Many anthropologists would immediately agree that such an observation is historically valid, but my ambition has been to give it a more literal significance than reflected in conventional acknowledgements that the emergence of industrial technology was conditioned by global processes (e.g. Marks, 2002; Wolf, 1982). The extent to which the industrialization of British textile production was contingent on global relations of exchange has been illuminated in detail by historians such as Joseph Inikori (2002) and Sven Beckert (2014). However, no matter how willing we are to concede that access to advanced technology represents a global, historical privilege, it will require a fundamental ontological shift to conceive of modern technology as such as a global societal phenomenon. To do so means acknowledging not only that the social is a product of the interpenetration of the local and the global, which is the hallmark of global perspectives, but also that technology is a product of the interpenetration of the material and the social. In the 1970s, the best tool I could find to articulate this perspective was the Marxist concept of fetishism. The place of fetishism, I had learned from Jonathan Friedman, is neither in the base nor the superstructure, but in ‘the center of the social formation’ (Friedman, 1974: 60). Such cultural perspectives on the material and ostensibly pragmatic practices of human societies have been my point of departure through decades of trying to achieve a truly anthropological approach to what I have called ‘machine fetishism’ (Hornborg, 1992).

The point I have been trying to make is that modern technologies that are contingent on price relations on the global market are socioecological phenomena that are as dependent on socially organized, asymmetric resource transfers as on revelations of the physical properties of nature. Rather than conceive of ‘the economy’ as sequestered from nature and ‘technology’ as sequestered from world society, our challenge is to grasp how our fetishized preoccupation with the manipulation of these two ostensibly unrelated kinds of artefacts—money and machines—adds up to a historically distinct mode of accumulation. In externalizing the appropriation of embodied human time and natural space in seemingly unassailable ways, what I call the ‘money–energy–technology complex’ defines the specific form of exploitation underlying modern civilization.

While the local/global interface has been explored and reconceptualized within world-system perspectives, the material/social interface implicates a range of
approaches within the sociology, history and philosophy of technology that have emerged out of the concept of ‘sociotechnical systems’ (Bijker et al., 1987), most fundamentally Latour’s (1993a) injunction against the purification of phenomena as either ‘social’ or ‘natural’. These latter approaches were largely established in the 1980s and 1990s, and they contributed to a renewed anthropological interest in technology and material culture. This was a period of significant progress in theorizing the social dimensions of technical artefacts, but I shall argue that the commitment to a case study approach has precluded a global understanding of the phenomenon of modern technology. While it is crucial to examine how local experience relates to global process, the ethnographer’s immersion in the former will not provide access to the logic of the latter. ‘Multi-sited ethnography’ will not solve the dilemma unless complemented with an abstract, theoretical grasp of how the dynamics of global systems in different ways shape local lifeworlds. Indeed, there can be no ‘ethnography of the global’.

To reconceptualize technology by transcending the distinction between the material/natural and the social poses a significant challenge for a global anthropology. It means understanding technological development not as a politically neutral potential inherent in nature—the uneven distribution of which is merely a result of historical contingencies—but as an intrinsically political and asymmetrically distributed phenomenon. In this view, technology is not a matter of progressively revealing nature’s possibilities—as if they were, in principle, accessible to all—but of accumulating, through asymmetric transfers of embodied labour and land, resources for harnessing forces in nature. To harness such forces—whether through steam, combustion, hydroelectric, nuclear or photovoltaic technologies—is not simply a feat of engineering but simultaneously also a capacity gained at the expense of the labour and resources of other parts of the global system. ‘Energy’ is ultimately a relational concept denoting natural forces that are available for human harnessing by means of a ‘technology’ that is itself relational in that it is contingent on capital accumulation representing asymmetric social transfers of resources. This means that the many interventions, since its conceptualization in the 19th century, calling for a greater emphasis on energy need to be complemented with the recognition that energy use is generally intertwined with asymmetries in social power—not just in the obvious sense that wielding more energy yields more power, but that access to energy in itself is contingent on capital accumulation. I shall begin by sketching the outlines of my argument, before more systematically discussing the insights and limitations of some early and foundational attempts to rethink the relation between technology and society.

The argument: technologies as material manifestations of global society

Methodologically, the reconceptualization of industrial technology as a global phenomenon is difficult to accomplish through conventional anthropological
fieldwork or even archival studies. The global processes that generate modern technologies cannot be exhaustively accounted for through local perspectives, regardless of where empirical investigations are conducted. Even the comparatively simple case of the 18th-century British steam engine implicates historical world market prices of a number of commodities, the rates at which several biophysical resources (including embodied labour) are exchanged, the balance sheets of various market actors, and so on.\textsuperscript{5} Inasmuch as modern technological systems are diffusely implicated in myriad market transactions throughout the world, they are interfused with the global social fabric and simply not amenable to the case study approach.

The discontinuity in material culture between pre-industrial tools, on the one hand, and industrial machines contingent on global market prices, on the other, appears to coincide with the emergence of a completely new form of technological rationality that has intrigued generations of social thinkers from Karl Marx through Jacques Ellul to Langdon Winner. This modern rationality, premised on a virtually unrestricted scope for ‘outsourcing’ or \textit{displacement} of resource requirements, is the local manifestation of the new logic of technology unleashed by the global economy since the late 18th century. Both as social practices and as concepts, ‘technology’ and ‘economy’ have emerged in tandem, recursively extending the scope for mobilizing human and natural resources to aggrandize the power of a global minority.

More fundamentally, a global, metabolic rethinking of technology requires a theoretical analysis that transcends not only historical, sociological and ethnographical narratives but also mainstream perspectives in engineering, economics, economic history, sociology and other social sciences. Rather than meticulous empirical demonstration, the perspective I am proposing requires a gestalt shift in perception. The bird’s-eye view afforded by a global satellite image of night-time lights is more conducive to such a gestalt shift than any amount of time spent interviewing engineers, stockbrokers, politicians, workers or African villagers. Across the social sciences, the commitment to empiricism and the case study approach precludes a genuinely global perspective on technology.

Paradoxically, our firmly entrenched inclination to insulate the material from the globally constituted social can be illustrated by none other than Karl Marx’s perception of early industrial machinery.\textsuperscript{6} In his deliberations on machinery, Marx approaches it as a \textit{local} consideration: ‘The use of machinery for the exclusive purpose of cheapening the product is limited by the requirement that less labour must be expended in producing the machinery than is displaced by the employment of that machinery’ (Marx, 1976 [1867]: 515). Although he is abundantly aware that labour and machinery are transposable in the sense that labour both produces and is displaced by machinery, and that this convertibility is made possible by money, Marx does not address the extent to which the existence of machinery is contingent on global exchange relations. The assumption appears to be that both types of labour—the labour expended in production of machinery and the labour displaced by it—have the same cost. The relative cost of labour in different geographical
areas or nations is not discussed as a factor influencing the adoption—not to mention the existence—of industrial machinery. Nor is the accumulation of machinery understood as contingent on flows of natural resources. Yet we know, for instance, that the annual British import of Swedish iron in the 1760s represented around a million hectares of Swedish forest and almost 14,000 person-year equivalents of Swedish labour (Warlenius, 2011: 68). The relative cost of British and Swedish land and labour should thus be a crucial consideration determining the extent of British investments in machinery in the 1760s. Such considerations of global price differences, and the asymmetric exchanges of embodied labour and land that they made possible, must not only have been fundamental to the feasibility of early industrialization in England but have continued to determine the conditions for technological development for two and a half centuries.

However, nowhere in the voluminous literature on the history, philosophy and sociology of technology have I found an indication of the profound implications that this should have for the very ontology of modern technology. The closest thing to such a paradigm shift that I have encountered is Andre Gunder Frank’s (1998: 204) insight that ‘technological development was a world economic process, which took place in and because of the structure of the world economy/system itself’. Such insights nevertheless tend to be compatible with an intact demarcation of the materiality of machines from the relationality of global exchange. Although solidly material, however, machines and technologies since the Industrial Revolution are relational phenomena in the sense that they exist only by virtue of exchange relations. The demarcation of the technological and the social is strengthened by the conventional conviction that technology is fundamentally a matter of knowledge of the physical properties of nature. But although engineering knowledge is a necessary condition for technology, it is not a sufficient one. Much as a biological genotype is not synonymous with an organism, a technical blueprint remains an abstraction until it is embodied in a metabolic process. The feasibility of the metabolic flows that sustain an organism is determined by its ecological context, whereas the feasibility of the metabolic flows that sustain a modern technology is determined by the world market. The reification and sequestration of the 18th-century British steam engine as an autonomous material artefact, contingent merely on the ingenuity of its inventors, was an illusion—as our category of ‘technology’ continues to be to this day. Its ultimate foundation was the social organization of the 18th-century world-system. Our inclination to objectify technology as detached (or excised, as it were) from its sociometabolic context is what I have referred to as ‘machine fetishism’. In reinserting the steam-driven textile factories of 19th-century England into the asymmetric metabolic flows of the triangular Atlantic trade, we can reinterpret them as social instruments for globally appropriating embodied human labour and natural space.

My use of the concept ‘sociometabolic’ highlights, again, that there are at least two conceptual demarcations that we need to transcend: not only the local versus the global as jointly constitutive of the social, but also the material versus the social as jointly constitutive of technology. As Bruno Latour, Tim Ingold and others
have argued, modern worldviews have suffered from a misleading dualism that distinguishes between society and nature as ontologically separate domains. Such dualism has constrained our capacity to recognize the mutual interpenetration of the social and the natural in tangible physical phenomena such as landscapes, bodies and technologies. Today few would deny that landscapes, bodies and technologies all have aspects that derive from both society and nature. In order to recognize their hybridity, however, it is crucial to retain the **analytical categories** of society and nature. To abandon conventional patterns of thought assuming the distinctness of the social and the natural, in other words, should not mean jettisoning the concepts themselves.

Our tendency to think of society and nature as domains that are insulated from each other has constrained our capacity to perceive social inequalities. Economists tend to disregard the role of nature in accounting for social processes (cf. Hall and Klitgaard, 2011; Martinez-Alier, 1987), while engineers tend to disregard the role of global society in accounting for the physical accomplishments of modern technology. Paradoxically, however, the post-humanist urge to jettison the categories ‘social’ and ‘natural’ also obscures social inequalities of power and distribution. The intermediate position advocated here is to recognize that the human reorganization of nature tends to be a way of physically establishing social inequalities. Much of what we conventionally perceive as nature is thus imbued with social organization, while society to a great extent builds on incontrovertibly natural phenomena. This, however, is not to downplay the importance of analytically distinguishing between those aspects of a process or object that derive from nature and those that derive from society.

Environmental historians know that domesticated landscapes everywhere reflect a social order: the layout of fields, buildings, roads and so forth mirror the organization of society. Anthropologists are similarly aware that human bodies everywhere reflect their positions in society: their occupation, diet, health and so on. In neither case would it be reasonable to deny that there is also a natural substratum, whether ecological or genetic. Technologies, finally, present us with the central problem in rethinking the relation between society and nature. In utilizing physical regularities such as the principles of thermodynamics, technologies obviously have natural aspects, but what exactly do we include in the common observation that they are also social phenomena? What does it mean to say that technologies are socially constructed (cf. Bijker et al., 1987)? It is obvious that technologies not only **reflect** their social contexts, performing specific functions that are in demand in those contexts, but conversely also mediate and **organize** social relations. Technologies may locally replace, reorganize and control labour, increase rates of profit, serve as tools of military conquest, and generally shape human mentalities and perceptions of reality. Such observations permeate studies of the history and sociology of technology, whether conducted within the traditions of the Social Construction of Technology (SCOT), 13 science and technology studies (STS), 14 Marxism, phenomenology or other contributions to the philosophy of technology. But none of these approaches acknowledges the extent to which technologies may
presuppose and embody specific patterns of social organization at the global level. They tend to focus on the specific designs and local human consequences of given technological systems but do not theorize their global societal prerequisites in terms of particular ratios of resource exchange on the world market. Yet it is clear that a given machine utilized in production represents a net input of physical resources, and that its output of commodities on the market must fetch exchange values in excess of those of the inputs of resources required to keep it running.

Building on Nicholas Georgescu-Roegen’s (1971) insight that economic processes enhancing utility simultaneously increase entropy, I have inferred that exchange values and productive potential must be inversely correlated, and that the uneven accumulation of technological infrastructure signifies the confluence of thermodynamics and imperialism (Hornborg, 1992). It would be unreasonable to deny that the principles of thermodynamics derive from nature, while the strategies of imperialism derive from global society. Clearly, however, mainstream economists are convinced that their accounts of growth and technological progress have no use for thermodynamics. In their worldview, nature is irrelevant for the constitution of society. No less myopic, however, is the inclination of mainstream engineers to believe that the accomplishments of technology are independent of the exchange rates organizing global resource flows. In their worldview, technology is tantamount to the revelation of nature and in no way contingent on the organization of society.

Whereas earlier efforts to theorize the social contexts and consequences of technology tend to relate a specific technological artefact to a restricted range of immediate users, the approach advocated here is to view its very existence as contingent on global social relations of exchange. I return to the example of the steam engine employed in British textile factories in the early 19th century. It owed its existence not only to the ingenuity of inventors like James Watt, but fundamentally also to the lucrative structures of exchange between Britain, West Africa and America. Without the trans-Atlantic flows of embodied African labour and embodied American land, and the African and American markets for British textiles, it is difficult to imagine a British Industrial Revolution (cf. Inikori, 2002). In the category ‘social’, as previously declared, I include the organization of the world-system, rather than restricting the concept of society to a national or local phenomenon. At this global level, technologies are indeed infused with social organization in a sense insufficiently acknowledged in conventional thought. Whereas other approaches to the social dimension of technology might focus, for instance, on the local social negotiations leading to the optimally designed engine, the factory owners’ use of steam engines to discipline labour, the use of steam engines as tools of British imperialism or workers’ experiences of labour in steam-driven factories, none of these approaches problematizes the ontology of technology itself. They assume the existence of an artefact like the steam engine as given by the strategies of engineers, capitalists and other human actors, reflecting their purposes and imposing their designs on other people, but they do not reflect on the steam engine as an embodiment of the world-system that made it possible to
begin with. Nevertheless, much as a living organism is a literal embodiment of the biophysical flows of energy and matter that sustain it, a functioning machine is an embodiment of biophysical resource flows, orchestrated by the distribution of money and constellations of market prices. Although many philosophers have emphasized that some material phenomena, such as living organisms, should be understood in relational terms—as manifestations of wider webs of relationships—this insight remains to be extended to the material existence of technological artefacts.

The identification of an industrial technology such as steam power with the asymmetric metabolic flows of the global social system that made it possible prompts us to rethink conventional narratives of industrialization and technological progress. The British shift from wool to cotton as the dominant raw material for textile production was tantamount to a vast displacement of land requirements from Britain to America, and the use of slave labour in the cotton plantations similarly entailed a displacement of workloads overseas. Although locally perceived as morally and politically innocent progress, from a global perspective the Industrial Revolution instead assumes the appearance of an asymmetric exchange of embodied labour time and a massive environmental load displacement.15 I have referred to such global processes underlying the Industrial Revolution as ‘time-space appropriation’ (Hornborg, 2006, 2013). My point is that the phenomenon of modern technology to a large extent can be conceptualized as a local saving of time and space at the expense of human time and natural space lost in other parts of the world-system.16

A common objection to this line of reasoning is that the technology ‘as such’ does not necessarily imply inequitable exchange relations or environmental load displacement. This was certainly the view held by Karl Marx, who predicted that the productive forces generated by capitalism could be extricated from their capitalist context and employed for collective benefit under socialism. He apparently perceived technology, understood as the enhancement of the productivity of local labour through the use of natural resources imported from elsewhere, as innocent ‘in itself’. Given more recent insights on the inextricable connections between material artefacts and their social contexts, however, such a detachment of a technology from the exchange relations that spawned it seems implausible even from a purely social-science perspective.17 To imagine the steam engine as detachable from asymmetric global resource flows indeed deserves to be referred to as ‘machine fetishism’. Extending Marx’s observations on money and commodity fetishism to the field of technology, I have proposed that machines, like money and commodities, are (global) social relations masquerading as things. This understanding of globalized technology becomes particularly evident when we consider the material metabolic flows of world trade. When a global satellite image of nighttime lights is juxtaposed with a world map showing gross domestic product (GDP) density per square kilometre, the two distribution patterns are virtually identical. The distribution of technomass coincides with the distribution of money. The accumulation of money is what has made the accumulation of
technology—and the displacement of work and environmental loads—possible. This is the essential—and necessarily global—logic of industrial capital. To understand advancing technology merely as a non-social revelation of nature is to perceive machines not as the social relations of asymmetric exchange that they represent, but as relations between things.

Drawing on thermodynamics, we must infer that the resource flows to and from industrial centres must be asymmetric in a physical sense, yet we know that this is not the way it looks to mainstream economists. The relation between the divergent perspectives of physics and economics is central to the reconceptualization of technology that I am proposing. It is incontrovertible that there was a massive net transfer of biophysical resources to Britain in the 1870s, yet the science of economics at this time established an approach to human economies that effectively disregarded the physical substance of traded commodities. The school of neoclassical economics, which achieved dominance in Britain in the 1870s, is exclusively concerned with exchange values (‘utility’) and flows of money. Its preoccupation with market mechanisms of supply and demand made the colonial appropriation of embodied labour, land, energy and materials invisible. The growth of technological infrastructure in Britain could thus be interpreted as the laudable product of ‘free’ trade, rather than as the accumulation of resources from its colonial empire. The challenge for British industry was to secure advantageous price relations on the world market. This could generally be achieved through various combinations of economic, political and military means, but in focusing on and objectifying the notion of ‘prices’, the worldview promulgated from now on would deny that the accumulation of technology presupposes asymmetric exchange. In other words, the new framing of such exchange—as the ‘free’ and morally neutral operation of market trade—enabled global structures of resource appropriation to survive the official end of colonialism. Neoclassical economic theory is an ideology originally developed in colonial Britain to justify and morally neutralize the exploitation of its extractive periphery. In its modern, neoliberal guise, it has championed ‘globalization’ as a modern euphemism for imperialism. The very concept of ‘technology’ is an indispensable component of this ideology.

To summarize, my general argument is that the globalized ensemble of technological artefacts is the physical scaffolding (the morphology, so to speak) of world society, and that the flows of money and resources are its physiology. The functions of engineering science and mainstream economics are to keep this global metabolism operating efficiently. In both respects, humans enlist physical materials and energy to organize their social inequalities, but in neither discipline are the ratios by which such physical resources are appropriated perceived as relevant to the validity and efficacy of its basic tenets. The implications of the observation that technologies are ‘socially constructed’ are very different depending on if we are merely concerned with their designs or with the asymmetric global transfers of material resources that make them possible.
Technology as the interpenetration of the material and the social: some formative contributions across the sciences

Having reiterated the basic outline of my argument, I shall now review some fundamental contributions from various fields that might serve as points of departure for an attempt to integrate an anthropology of technology with an anthropology of global systems. The role of technology in human societies has been a central focus of two and a half centuries of reflections on social change, beginning with the dramatic transformations of society in 19th-century England. Whether celebrated as progress or demonized as destructive of human values, technological development has been recognized as inextricably intertwined with the organization of society and human consciousness.\(^{20}\) The ambivalent attitudes towards technology are apparent in Robert Post’s (2010) reflections on 50 years of the Society for the History of Technology (SHOT) and its journal *Technology and Culture*. Although aspiring to transcend the technical interests of mainstream engineers and antiquarians, there were nevertheless deep concerns in 1959 that the word ‘culture’ would deter engineers from subscribing. In the deliberations that finally settled on including the concept in the journal title, advocates referred to iconic anthropologists such as Margaret Mead, Ruth Benedict and even Edward Tylor.\(^{21}\) According to the historian Melvin Kranzberg, who founded *Technology and Culture*, its title reflects ‘the broad sociological, anthropological, economic, and humanistic content of the journal’ (Post, 2010: 977). There was clearly an awareness that there is more to technology than the technical, and that it should not simply be left to engineers.

In retrospect, the new society and journal were compelled to strike a balance between criticism and public acceptance. Early contributors to the journal included wide-ranging, critical and often pessimistic writers like Lewis Mumford, Jacques Ellul, Lynn White, Jr., Walter Ong, Kenneth Boulding, Thomas Hughes, Joseph Needham, Aldous Huxley and Wernher von Braun. It seems that the kinds of humanistic and ecological criticism of technology delivered by these people—such as in the special issue of *Technology and Culture* devoted to the records of the ‘Encyclopedia Britannica Conference on the Technological Order’ (Stover, 1962)—were finally not subversive enough to be incompatible with Kranzberg’s success in ‘enlisting support from a wide array of academic notables’ (Post, 2010: 979) including Thomas Kuhn, David Riesman, Robert Merton and Peter Drucker. In successfully seeking allies ‘from beyond academe in engineering and industry’ (Post, 2010: 979), *Technology and Culture* could obviously not be seriously subversive. Its vision was to reveal the sociocultural contexts of technological development, but only with regards to humanistic concerns or the designs of specific technologies, never in the sense of identifying the asymmetric global metabolic flows on which technology as a whole is contingent. By means of an ironic illustration of the very sequestration of technology from society that these and subsequent critics have pervasively addressed, ‘technology’ to this day remains a
legitimate target of critique, as long as the criticism is not extended to the social organization (the capitalist world market) that it embodies.\(^{22}\)

Forty years ago, Langdon Winner (1977) summarized some core concerns of philosophers of technology such as Marx, Heidegger, Mumford, Ellul and Marcuse. For two centuries, a pervasive theme among philosophers and people in general has been the apprehension that technological change is a process beyond social control, pursuing its own autonomous logic rather than answering to the wishes of humans. Winner traces recurrent worries that humans are becoming the servants of machines, rather than their masters. Common to these humanistic concerns is the observation that technical devices tend to have significant and often unanticipated consequences for social relations among the people who use them. In a later book explicitly critical of the political aspects of technology, Winner (1986) begins by observing that human lives are shaped by an interconnected technological order that ‘transcends national boundaries’, yet generally illustrates his ‘political philosophy of technology’ with American examples.\(^{23}\) Like his predecessors from Marx to Marcuse, Winner is concerned with how technologies shape the lives, minds and societies of those who have access to them, rather than with how they shape *global* relations between those who do and those who don’t. However, his focus on how material culture embodies and reproduces social relations of power and inequality can be extended to include such global considerations. Winner’s ‘epistemological Luddism’ (1977: 330) is not reducible to ‘blaming the hardware’ (1986: ix–x) but recognizes that sociotechnical systems frequently have political implications.

A foundational volume edited by Wiebe Bijker, Thomas Hughes and Trevor Pinch (1987) gathered several detailed case studies of the sociological processes that have shaped particular technologies. In the same year, Bruno Latour (1987) published a volume that was to become paradigmatic for the methodological approach of STS. Both books represent a shift of focus from the traditional concern with the social consequences of technology to how technologies are shaped by society. The chapter by Pinch and Bijker (1987) in the former volume offers an influential sociological methodology for studying the ‘social construction of technology’. Hughes’ (1987) chapter introduces the concept of ‘sociotechnical systems’, which analytically integrates the social and the technological.\(^{24}\) Michel Callon’s (1987) chapter outlines the basic tenets of actor–network theory (ANT), an approach closely aligned with that of Latour, which controversially claims that technical artefacts and other inanimate factors have agency in much the same way that humans and other living beings do. Also pioneering the ANT approach, John Law’s (1987) chapter discusses the role of naval technology in Portuguese maritime expansion in the 15th and 16th centuries.

In this same year, Latour and primatologist Shirley Strum (Strum and Latour, 1987) published a co-authored paper that argued that the reason why humans can build more permanent and extensive societies than baboons is that humans can stabilize their social relations by anchoring them to artefacts of various kinds. This perspective is fundamental to Latour’s later work on the role of technical artefacts as mediators of human social relations.
An anthropology of technology?

This is also the time when anthropologists, after decades of silence, begin to express a renewed interest in technology and material culture. In ‘an excursion in the philosophy of technology’, originally published 1988, Tim Ingold (2000: 311), drawing on Marx, reflects on how the transition from skill- and tool-based manufacture to machines and dehumanizing ‘machinofacture’ involved ‘a progressive objectification and externalization of the productive forces’ (emphasis in original). The following year, in a paper originally published in 1990, Ingold unravels and problematizes how ‘technical relations have become progressively disembedded from social relations, leading eventually to the modern institutional separation of technology and society’ (Ingold, 2000: 321–322). He writes:

Having thus been placed outside of society and culture, technology could—so far as most anthropologists were concerned—be safely ignored. It was considered to be just one of those things, like climate or ecology, that may or may not be a determining factor in human affairs, but whose study can be safely left to others. As climate is for meteorologists and ecology for ecologists, so technology is for engineers (Ingold, 2000: 313).

More or less simultaneously, Bryan Pfaffenberger (1988a: 236) proposed an ‘anthropology of technology’ that views technology as ‘a total social phenomenon in the sense used by Mauss; . . . simultaneously material, social and symbolic’. He suggested that the modern concept of technology—‘a term that stands, arguably, at the very centre of what Westerners (and Westernised people) tend to celebrate about themselves’—is a ‘mystifying force of the first order’, denoting a variety of fetishism concomitant to the fetishism of commodities revealed by Marx (Pfaffenberger, 1988a: 237, 250). Pfaffenberger attributes to Marx the ‘extraordinary anthropological insight [that] the Western ideology of objects renders invisible the social relations from which technology arises and in which any technology is vitally embedded’ (Pfaffenberger, 1988a: 242; emphasis in original). A recurrent theme in Pfaffenberger’s papers from this period is that traditional Hindu temples in Sri Lanka can be understood as a kind of technology no more mystical than a modern machine (Pfaffenberger, 1988b). Drawing on Latour and ANT, he suggests that the Industrial Revolution was fundamentally about replacing ‘ritual machinations like the temple’ with ‘kinematic machinations such as the windmill or watermill’ (Pfaffenberger, 1988b: 15). Like other sociotechnical systems, the temple regularizes and disciplines human behaviour. In a subsequent review article, Pfaffenberger (1992) advocates a renewed anthropological interest in technology and material culture building on the concept of ‘sociotechnical systems’ as applied by Hughes (1987), Latour (1987) and Law (1987):

As it stands, a topic with which anthropology was once closely identified—the cross-cultural study of technology and material culture—has been largely taken up by
scholars working in other fields, such as the history of technology and the interdisciplinary field known as science and technology studies (STS) (Pfaffenberger, 1992: 492).

Pfaffenberger declares that the central objective of his review article is to ‘convey the sociotechnical system concept to an anthropological audience’, a concept that ‘refuses to deny the sociality of human technological activity’ (Pfaffenberger, 1992: 493; emphasis in original).

With an edited collection of case studies published the following year, Pierre Lemonnier (1993) encouraged anthropologists to approach technologies as complex sociocultural phenomena that extend far beyond the merely technical. The collection includes chapters by Ingold, Pfaffenberger and Latour. Latour’s (1993b) chapter reflects on his 1988 study of the negotiations around the aborted subway project Aramis, planned to integrate southern Paris. In contrast to primate societies like the baboons he studied with Shirley Strum, he concludes, human societies are stabilized by the delegation of tasks to non-human components:

Techniques are not something around which there is a society. It [sic] is society considered in its obduracy. It is society folded, society made durable, society made complicated in order to resist more tensions by enrolling more non-humans... Although this folding, this detour, this shifting down, this embedding is clear in anthropologists’ accounts of exotic technologies, it is not so obvious in modern high-tech cases (Latour, 1993b: 379–380; emphasis in original).

Deploring that social scientists have ‘used the Durkheimian model on everything but science and technology’, Latour argues for an extension of ‘social constructivism to science and technology’ (Latour, 1993b: 392–394; emphasis in original).

In the same year, Langdon Winner countered that the empiricism of social constructivism is not conducive to ‘one’s ability to talk in penetrating, reliable ways about modern technology in general’ (Winner, 1993: 363; emphasis added). Its rejection of ‘the abstract speculations of philosophers’ such as Marx, Ellul, Heidegger, Mumford and Illich in favour of detailed empirical case studies tends to lead to a disregard not only for the social consequences of a given technology, but also for issues regarding ‘the broader distribution of power in society’ (364, 368). Winner criticizes social constructivism for providing ‘no solid, systematic standpoint or core of moral concerns from which to criticize or oppose any particular patterns of technical development’, and for implicitly subscribing to the view that ‘what matters in the end is simply the exercise of raw power’ (374). According to Winner, the projects of social constructivists are ‘carefully sanitized of any critical standpoint that might contribute to substantive debates about the political and environmental dimensions of technological choice’, risking a retreat into ‘a blasé, depoliticized scholasticism’ (375–376). A quarter of a century later, Winner’s indignation rings truer than ever. His persistent observation that a given
technology that provides benefits to some may cause harm to others should be extended to the global metabolism of modern technology as such.

We have traced the emergence and consolidation, in the 1980s and 1990s, of an interdisciplinary discourse that scrutinizes how specific technological artefacts are imbued with social relations, symbols, ideas, intentions, even politics, but that completely ignores the question of how the very phenomenon of technology as a whole operates as a sociometabolic system for organizing and reproducing power and inequalities in global society. While the anthropology of technology has generally applied perspectives similarly constrained by the case study approach, a global anthropology capable of transcending the distinction between the social and the material might recognize the planetary technomass as the physical scaffolding that buttresses or ‘stabilizes’ the structure of world society. Ultimately, the most significant ‘sociotechnical system’ is nothing less than the global system.29

Why acknowledging globalized technology as a total sociometabolic phenomenon is too subversive

The contributions reviewed so far, whether by philosophers, historians, sociologists or anthropologists, have all shared the insight that technology represents the interpenetration of the material and the social. In the restricted sense explored by social constructivism, this was already established 30 years ago. However, in none of these four intersecting fields—the philosophy of technology, the history of technology, sociological studies of science and technology, and the anthropology of technology and material culture—have I found a concern with the global distributive dimension of the sociometabolic phenomenon of modern technology as such. The question was not a concern of any of these fields 30 years ago, nor has it become a concern for any of them in the time that has elapsed since then. This conclusion is based on perusal of several texts that can be expected to reflect the diversity of topics within their respective fields, whether the philosophy of technology (Ihde, 1993, 2010; Kirchhoff, 2009; Lawson, 2008; Mitcham, 1994; Scharff and Dusek, 2014), the history of technology (Headrick, 2009; Nye, 2006; Smith and Marx, 1994), science and technology studies (Ihde and Selinger, 2003; Latour, 2005), or the anthropology of technology and material culture (Lemonnier, 1993; Miller, 1987, 2005; Spyer, 1998). If anything, these fields dedicated to the academic analysis of material artefacts have moved even further away from overriding, critical political and moral concerns with the role of technology in the contemporary world.30 Are affluent modern people now simply too accustomed to living in a thoroughly technologized society to reflect on its specific conditions?31 Upon browsing through the pages of recent deliberations on ‘technoscience’ or ‘materiality’, it soon becomes evident that the asymmetric global resource flows that ultimately condition these myriad local engagements with artefacts are not matters of concern for mainstream social theories of technology and material culture.32
How can we account for this? I can think of three contributing factors:

1. The conceptual constraints of the case study approach continue to shape our discourse on technology. Regardless of discipline, we tend to assume that technologies are aspects of local social organization and should be studied in those terms. We continue to study sociotechnical systems as instances of a universal human embeddedness in an immediate world of artefacts, but do not scrutinize the category—or global societal conditions—of modern technology as such. The global social order manifested in our increasingly globalized technologies is taken for granted.

2. The concern with how material artefacts are shaped and organized by social relations and cultural conceptions—and vice versa—only superficially transcends dualisms such as mind versus matter or society versus nature. Beyond recognizing the recursive interaction between the materiality of technology and society, a more demanding challenge is to understand global society itself as in significant respects materially constituted. To address the ‘social construction of technology’ in the conventional sense established in the 1980s is to disregard the capacity of world society to reorganize and redistribute the material conditions for engineering. Only by including the material operation of the world economy in the concept ‘social’ can we grasp how modern industrial technology as a whole is ‘constructed’ through asymmetric global exchanges of biophysical resources. Such an interdisciplinary, sociometabolic perspective will no doubt seem alien to most social scientists.

3. The conclusion that modern technology is an inextricable component of an obscenely unequal and exploitative world order is an offence not only against centrally positioned academic fields such as economics and engineering, but ultimately also against the interests of global capitalism. It can thus safely be predicted that more or less subtle processes of selection and exclusion will guarantee that such a perspective will never become a part of mainstream discourse. A likely reaction to the argument presented here is that its implications would simply be bewildering. But however powerful they are in determining discursive closure, such pragmatic objections are political, not theoretical.

If not simply bewildering, what might the practical implications of this theoretical argument be for our approach to modern technology? The most obvious implication is undoubtedly that both mainstream and Marxist visions of a shift to low-carbon technologies to mitigate climate change are founded on misleading assumptions about what technologies really are. When David Ricardo asserted that capital could substitute for land, he codified the outlook of wealthier nations able to displace their ecological footprints to other parts of the global system. To say, two centuries later, that solar-power infrastructures require substantial investments of capital is a convoluted way of saying that they have great indirect requirements on embodied land and labour appropriated from elsewhere. Whether it is feasible to procure such volumes of embodied resources from other parts of the world depends
on relative market prices of human time and natural space. The global economy is currently propelled to almost 90% by fossil energy, which means that the construction of non-fossil infrastructures like hydroelectric, nuclear and solar is itself fossil-fuelled to the same extent. The hype about a transition to renewable energy is an illusion, because the annual expansion of such energy use remains slower than the expansion of the use of fossil fuels. Nor is the world economy ‘dematerializing’ (Schandl et al., 2016). We very urgently need to understand why our technological visions are not being implemented. This is an ontological cataclysm that we cannot for long circumvent. These are uncomfortable challenges, to be sure, but to choose not to address them should not be an option for anthropological theory.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

ORCID iD

Alf Hornborg https://orcid.org/0000-0003-2102-5875

Notes

1. Parts of this article overlap with chapter 6 in my book Nature, Society, and Justice in the Anthropocene (Hornborg, 2019).
2. I had the good fortune of being Jonathan Friedman’s and Kajsa Ekholm Friedman’s student in Lund between 1974 and 1978. They were both keen on interpreting archaeological, historical and contemporary data in terms of structural transformations generated within ‘total systems of social reproduction’.
3. By ‘ontological’ I mean pertaining to how we perceive the fundamental essence or rationale of a phenomenon. Here I argue for a fundamental shift from the conventional view that technological development is a matter of putting nature to work to the conclusion that it is a strategy of putting other sectors of the global social system to work.
4. It is incumbent on me to begin by defining what I mean by ‘technology’. In this article, I will restrict the definition to a system of material artefacts that locally augments the capacity of a certain social category in some respect (e.g. by reducing necessary expenditures of human time), while being contingent on the rates at which biophysical resources (including embodied labour) are exchanged on the world market. It should be observed that most pre-industrial artefacts do not meet the latter criterion.
5. Joseph Inikori (1989: 367–369) has demonstrated that ‘the conditions for the technological innovations in the [cotton textile] industry in the late eighteenth century’ were created by ‘the production of cotton textiles for the slave trade in Africa and for the clothing of the African slaves on the New World plantations’. This observation provides
a welcome counter-narrative to Eurocentric historiographies of technological progress, but—unless combined with theoretical insights on ‘sociotechnical systems’ (cf. Hughes, 1987; Pfaffnerberger, 1992)—does not in itself transform our ontological framing of technology. Even explicitly non-Eurocentric historiographies of technology (e.g. Blaut, 2000) tend to focus on the non-European origins of particular innovations, rather than on technologies as components of systems of social reproduction that transcend Europe.

6. This is paradoxical because Marx himself pioneered the theoretical integration of the material and the social, as in his understanding of machinery as ‘congealed labour’, but did not sufficiently acknowledge the global societal context of technological development. His focus was on production, but he rarely asked for whom (i.e. for which markets) production occurred, or from where derived the labour and land embodied in raw materials such as cotton fibre. In this respect, Inikori’s (1989, 2002) research on the globalized incentives for—and prerequisites of—British mechanization is an important corrective to the myopic Marxist concept of ‘productive forces’.

7. Neither has Emmanuel’s (1972) analysis of the unequal exchange of embodied labour in world trade contaminated the Marxist perception of technology. To enhance the productivity of local labour by means of technologies that are contingent on net transfers of resources and embodied labour from elsewhere thus continues to be viewed by Marxists as a fundamentally beneficial process leading ultimately to socialism.

8. Statistics on world trade converted from monetary to biophysical metrics reveal that net imports to the wealthiest core areas of the world-system (USA, EU and Japan) in 2007 totalled around 12.6 gigatons of raw material equivalents, 34 exajoules of embodied energy, 5.6 million square kilometres of embodied land and 247 million person-year equivalents of embodied labour (Dorninger and Hornborg, 2015). As all three areas were net importers of all four resources, the statistics show that it was not simply a matter of specialization, with different areas exchanging different kinds of resources with each other, but of a net transfer of all four resources contributing to the accumulation of global ‘technomass’ (i.e. technological infrastructure) as a whole.

9. A representative definition of technology by a centrally positioned authority on its ontology is Wiebe Bijker’s (2010: 64) assertion that it ‘comprises, first, artefacts and technical systems, second the knowledge about these and, third, the practices of handling these artefacts and systems’. How, one wonders, do exchange relations on the global market—distributing the material resources that are requisite for the technology to exist—at all enter the picture? Michel Callon (1987: 90, 94) briefly touches on the issue when he mentions the market prices of oil and metals as included among the various ‘forces’ or ‘actors’ that influenced the competition between rival automobile designs in France in the 1970s, but the acknowledgement of market factors does not prompt him to rethink technology as fundamentally a matter of distribution. Callon’s (1998) edited volume on the sociology of markets—which, like Latour, frequently evokes anthropology—similarly deals with the conditions of ‘calculative agency’, rather than the asymmetric material flows generated by discrepancies between the substance and the price of commodities. Given the professed concern of actor–network studies with the material outcome of processes involving the interaction of human and non-human entities, this is a significant omission.

10. Although several authors (e.g. Pomeranz, 2000; Wilkinson, 1973) have acknowledged that the Industrial Revolution entailed a British displacement of resource demands overseas, such insights do not seem to have contaminated their fundamental conception of technology.
11. Cf. Layton (1974); Mitcham (1994: 192–208). Ingold (1997: 130) captures this modern conception of technology as ‘the means by which a rational understanding of [the] external world [of nature] is turned to account for the benefit of society’.

12. By ‘sociometabolic’, I refer to the flows of matter and energy that are socially organized and physically sustain a social system. The concept of social metabolism is well established in fields such as ecological economics and industrial ecology. Foster (2000) traces its roots to Karl Marx, but the Marxist understanding of ‘productive forces’, in failing to pursue the implications of the fact that industrial technology is contingent on global ‘relations of production’, tends to reproduce mainstream machine fetishism as theorized here.

13. See Bijker et al. (1987).

14. E.g. Latour (1987).

15. In 1850, a sale of British cotton manufactures on the world market for £1000, and the purchase of raw cotton for the same amount, would have been tantamount to exchanging 14,233 hours of embodied British labour for 20,874 hours of Afro-American labour, and of less than a hectare of embodied British land for 58.6 hectares of American land (Hornborg, 2013).

16. In terms of ‘the black box’ evoked by Pinch and Bijker (1987) and Winner (1993: 365), a modern technology in this view is a device for converting inputs of human time and natural space deriving from one social category into outputs in the form of power (e.g. a liberation of time and space) for another.

17. For an early and foundational statement of this perspective, albeit regrettably not concerned with asymmetric material flows, see Bijker et al. (1987).

18. From the mainstream economic perspective on international trade, poverty (low wages) and environmental abuse (lax environmental legislation) are to be viewed as ‘comparative advantages’.

19. For a discussion of how different schools of economic thought have served to justify different historical injustices, see Ruggiero (2013).

20. There have even been attempts to understand the historical development of technology as a fundamentally religious pursuit (Noble, 1999).

21. See also appeals to anthropology by the historian John Staudenmaier (1984: 708) and the self-declared ‘engineer-turned-sociologist’ Wiebe Bijker (2010: 63). It is interesting to note that historians and engineers seem to have been more enthusiastic about an ‘anthropology of technology’ than were anthropologists themselves (see below).

22. Reflecting on 25 years of SHOT and Technology and Culture, Staudenmeier (1984: 722) notes ‘the complete absence of a Marxist perspective’ and the striking omission of discussions on ‘the influence of capitalism on technology’. This is no doubt related to his finding that, of 272 articles published in the first two decades of the journal’s existence, only two consider ‘non-Western technologies from a contextual perspective’ (Staudenmeier, 1984: 722). Twenty-five years later, his critical assessment is echoed by Wiebe Bijker (2009).

23. In the chapter titled ‘Do artifacts have politics?’ Winner (1986: 22–23) shows that the low bridges over parkways on Long Island, New York, were deliberately designed to exclude buses (and their lower-class passengers) from a public park.

24. For a retrospective appraisal of the consolidation of SCOT and the significance of the concept of the ‘sociotechnical’, see Bijker (2010).

25. In a later paper, Ingold (1997: 108) demonstrates how this understanding of the historical emergence of a concept of disembedded ‘technology’ is completely parallel to anthropological analyses of the emergence of the disembedded ‘economy’.
26. While it is incontrovertible that traditional Hindu temples integrated complex socio-technical systems—illustrating the premodern embeddedness of technical relations in social relations highlighted by Ingold—this is precisely not equivalent to saying that temples are machines (in Ingold’s sense).

27. Pfaffenberger (1988b: 14; 1992: 510) cites Latour’s (1987: 129) apposite definition of a machine as ‘first of all a machination, a stratagem, a kind of cunning’.

28. Upon searching the internet for contributions to an ‘anthropology of technology’, I have found very little beyond those of Ingold, Pfaffenberger and Lemonnier dating to the 1980s and 1990s. A possible explanation is that the insight that specific systems of technical artefacts must be understood as embedded in social relations and cultural frames of mind (i.e. that they should be approached as sociotechnical systems) is so obvious that it no longer needs to be asserted. Indeed, by the early 1990s, Winner (1993: 376) already felt that constructivists had been repeating their point about the social context of technological development ‘ad nauseam’.

29. While Mumford’s slave-propelled ‘megamachines’ of antiquity and the modern world-system are both sociotechnical systems, we are currently unable to see how technologies in the latter case are as contingent on power inequalities as in the former.

30. For example, Ihde (2010: 29–30) observes that mention of ‘dystopian godfathers’ such as Ellul, Heidegger, Mumford and Marx have mostly disappeared from contemporary philosophy of technology.

31. Perhaps we need to remind ourselves that, if European or American lifestyles were universalized, it would require four additional planets. To exemplify the technological implications of global inequalities, the scale of Euro-American access to inexpensive electronic devices made in China is clearly contingent on abysmal global wage differences. Even more disconcerting, almost one-third of humanity must survive on less than US$2 per day, which obviously means having access to no technology whatsoever. Against this background, it is difficult to be enthusiastic about esoteric discourses on the complex ways in which Euro-Americans experience the privileged world of gadgets in which they are immersed. It can be genuinely depressing to see generations of talented social scientists spending their intellectual energy on everything but the global society they might be struggling to comprehend.

32. It is noteworthy that anthropological discourses on materiality are completely oblivious of studies of global material flows, which demonstrate, for instance, that there is an annual net transfer of many gigatons of materials to the US, EU and Japan from the rest of the world (Dorninger and Hornborg, 2015), that the material intensity of the global economy has increased over the past decade, and that if the trend continues the world’s population will require almost three times as much materials in 30 years’ time (Schandl et al., 2016). Discourses on the phenomenology and the politics of materiality and material culture appear to be completely insulated from each other.

References

Beckert S (2014) Empire of Cotton: A Global History. New York: Vintage Books.

Bijker WE (2009) Globalization and vulnerability: Challenges and opportunities for SHOT around its fiftieth anniversary. Technology and Culture 50(3): 600–612.

Bijker WE (2010) How is technology made? That is the question! Cambridge Journal of Economics 34(1): 63–76.
Bijker WE, Hughes TP and Pinch TJ (eds) (1987) *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*. Cambridge: The MIT Press.

Blaut JM (2000) *Eight Eurocentric Historians*. New York, NY: The Guilford Press.

Callon M (1987) Society in the making: The study of technology as a tool for sociological analysis. In: Bijker WE, Hughes TP and Pinch TJ (eds) *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*. Cambridge: The MIT Press, pp. 83–103.

Callon M (ed) (1998) *The Laws of the Markets*. Oxford, UK: Blackwell Publishers.

Dorninger C and Hornborg A (2015) Can EEMRIO analyses establish the occurrence of ecologically unequal exchange? *Ecological Economics* 119(November): 414–418.

Emmanuel A (1972) *Unequal Exchange: A Study of the Imperialism of Trade*. New York: Monthly Review Press.

Foster JB (2000) *Marx’s Ecology: Materialism and Nature*. New York: Monthly Review Press.

Frank AG (1998) *ReOrient: Global Economy in the Asian Age*. Berkeley: University of California Press.

Friedman J (1974) The place of fetishism and the problem of materialist interpretations. *Critique of Anthropology* 1(1): 26–62.

Georgescu-Roegen N (1971) *The Entropy Law and the Economic Process*. Cambridge: Harvard University Press.

Hall CAS and Klitgaard KA (2011) *Energy and the Wealth of Nations: Understanding the Biophysical Economy*. New York: Springer.

Headrick DR (2009) *Technology: A World History*. Oxford, UK: Oxford University Press.

Hornborg A (1992) Machine fetishism, value, and the image of unlimited good: Toward a thermodynamics of imperialism. *Man (N.S.*) 27 (1): 1–18.

Hornborg A (1998) Towards an ecological theory of unequal exchange: Articulating world system theory and ecological economics. *Ecological Economics* 25(1): 127–136.

Hornborg A (2001) *The Power of the Machine: Global Inequalities of Economy, Technology, and Environment*. Walnut Creek: AltaMira Press.

Hornborg A (2006) Footprints in the cotton fields: The Industrial Revolution as time-space appropriation and environmental load displacement. *Ecological Economics* 59(1):74–81.

Hornborg A (2013) *Global Ecology and Unequal Exchange: Fetishism in a Zero-Sum World*. Revised paperback version. Abingdon: Routledge.

Hornborg A (2019) *Nature, Society, and Justice in the Anthropocene: Unraveling the Money-Energy-Technology Complex*. Cambridge: Cambridge University Press.

Hughes TP (1987) The evolution of large technological systems. In: Bijker WE, Hughes TP and Pinch TJ (eds) *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*. Cambridge: The MIT Press, pp. 51–82.

Ihde D (1993) *Philosophy of Technology: An Introduction*. New York: Paragon House.

Ihde D (2010) Philosophy of technology (and/or technoscience?): 1996–2010. *Techné* 14(1): 26–35.

Ihde D and Selinger E (2003) *Chasing Technoscience: Matrix for Materiality*. Bloomington: Indiana University Press.

Ingold T (1997) Eight themes in the anthropology of technology. *Social Analysis: The International Journal of Social and Cultural Practice* 41(1): 106–138.
Ingold T (2000) *The Perception of the Environment: Essays in Livelihood, Dwelling and Skill*. London: Routledge.

Inikori JE (1989) Slavery and the revolution in cotton textile production in England. *Social Science History* 13(4): 343–379.

Inikori JE (2002) *Africans and the Industrial Revolution in England: A Study of International Trade and Economic Development*. Cambridge: Cambridge University Press.

Kirchhoff MD (2009) Material agency: A theoretical framework for ascribing agency to material culture. *Techné* 13(3): 206–220.

Latour B (1987) *Science in Action: How to Follow Scientists and Engineers through Society*. Cambridge: Harvard University Press.

Latour B (1993a) *We Have Never Been Modern*. Cambridge: Harvard University Press.

Latour B (1993b) Ethnography of a “high-tech” case: About Aramis. In: Lemonnier P (ed.) *Technological Choices: Transformation in Material Cultures since the Neolithic*. Abingdon: Routledge, pp. 372–398.

Latour B (2005) *Reassembling the Social: An Introduction to Actor-Network-Theory*. Oxford: Oxford University Press.

Law J (1987) Technology and heterogeneous engineering: The case of Portuguese expansion. In: Bijker WE, Hughes TP and Pinch TJ (eds) *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*. Cambridge: The MIT Press, pp. 111–134.

Lawson C (2008) An ontology of technology: Artefacts, relations and functions. *Techné* 12(1): 48–64.

Layton ET Jr (1974) Technology as knowledge. *Technology and Culture* 15(1): 31–41.

Lemonnier P (ed.) (1993) *Technological Choices: Transformation in Material Cultures since the Neolithic*. Abingdon: Routledge.

Marks RB (2002) *The Origins of the Modern World: A Global and Environmental Narrative from the Fifteenth to the Twenty-first Century*. Lanham: Rowman & Littlefield.

Martinez-Alier J (1987) *Ecological Economics: Energy, Environment and Society*. Oxford: Blackwell Publishers.

Marx K (1976 [1867]) *Capital*, vol.1. London: Penguin Books.

Miller D (1987) *Material Culture and Mass Consumption*. Oxford: Blackwell Publishers.

Miller D (ed) (2005) *Materiality*. Durham: Duke University Press.

Mitcham C (1994) *Thinking through Technology: The Path between Engineering and Philosophy*. Chicago: The University of Chicago Press.

Noble DF (1999) *The Religion of Technology: The Divinity of Man and the Spirit of Invention*. London: Penguin Books.

Nye DE (2006) *Technology Matters: Questions to Live With*. Cambridge: The MIT Press.

Pfaffenberger B (1988a) Fetishised objects and humanized nature: Towards an anthropology of technology. *Man (N.S.)* 23(2): 236–252.

Pfaffenberger B (1988b) The Hindu *Akama* temple as a machine, or, the Western machine as a temple. Paper presented at the Department of Cultural Anthropology, Uppsala University.

Pfaffenberger B (1992) Social anthropology of technology. *Annual Reviews in Anthropology* 21(1): 491–516.

Pinch TJ and Bijker WE (1987) The social construction of facts and artifacts: Or how the sociology of science and the sociology of technology might benefit each other. In: Bijker
WE, Hughes TP and Pinch TJ (eds) *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*. Cambridge: The MIT Press, 17–50.

Pomeranz K (2000) *The Great Divergence: China, Europe, and the Making of the Modern World Economy*. Princeton: Princeton University Press.

Post RC (2010) Back at the start: History and technology and culture. *Technology and Culture* 51(4): 961–994.

Ruggiero V (2013) *The Crimes of the Economy: A Criminological Analysis of Economic Thought*. Abingdon: Routledge.

Schandl H, Fischer-Kowalski M, West J, et al. (2016) *Global Material Flows and Resource Productivity: An Assessment Study of the UNEP International Resource Panel*. Paris: United Nations Environment Programme.

Scharff RC and Dusek V (eds) (2014) *Philosophy of Technology: The Technological Condition–An Anthology*. Malden: Wiley Blackwell.

Smith MR and Marx L (eds) (1994) *Does Technology Drive History? The Dilemma of Technological Determinism*. Cambridge: The MIT Press.

Spyer P (ed.) (1998) *Border Fetishisms: Material Objects in Unstable Spaces*. Abingdon: Routledge.

Staudenmaier JM (1984) What SHOT hath wrought and what SHOT hath not: Reflections on twenty-five years of the history of technology. *Technology and Culture* 25(4): 707–730.

Stover CF (ed) (1962) *The Encyclopedia Britannica Conference on the Technological Order*. Special issue of Technology and Culture.

Strum SS and Latour B (1987) Redefining the social link: From baboons to humans. *Social Science Information* 26(4): 783–802.

Warlenius R (2011) *Iron for Tea: The Trade of the Swedish East India Company as a Cross-Continental Case Study of Ecologically Unequal Exchange in the Eighteenth Century*. Master Thesis, Department of Economic History, Stockholm University.

Wilkinson RG (1973) *Poverty and Progress: An Ecological Model of Economic Development*. London: Methuen.

Winner L (1977) *Autonomous Technology: Technics-out-of-Control as a Theme in Political Thought*. Cambridge: The MIT Press.

Winner L (1986) *The Whale and the Reactor: A Search for Limits in an Age of High Technology*. Chicago: The University of Chicago Press.

Winner L (1993) Upon opening the black box and finding it empty: Social constructivism and the philosophy of technology. *Science, Technology, and Human Values* 18(3): 362–378.

Wolf ER (1982) *Europe and the People Without History*. Berkeley: University of California Press.

**Alf Hornborg** is an anthropologist and Professor of Human Ecology at Lund University, Sweden. His research has addressed the cultural and political dimensions of human–environmental relations in past and present societies. A central contribution is to understand ‘ecologically unequal exchange’ as fundamental to the existence of modern technology, as theorized in *The Power of the Machine* (2001), *Global Ecology and Unequal Exchange* (2011), *Global Magic* (2016) and *Nature, Society, and Justice in the Anthropocene* (2019).