Elemental computation: from nonhuman media to more-than-digital information systems

Authors

Bronislaw Szerszynski and Nigel Clark (Lancaster University)

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Abstract: Pervasive, high-powered digital information processing has been instrumental in turning the Earth and its constitutive systems into an object of thought and practice. But how does digitized informatics look when we approach it as process that emerged *out of* and *through* the dynamic planetary body we inhabit? In this chapter we review work that has probed and troubled the division between the domain of 'abstract', 'disembedded', 'dematerialized' information systems and the 'stuff' of the material world. We argue that human informatic technologies capture and elaborate upon information processing capabilities that inhere in the Earth's physical systems – both organic and inorganic.

Keywords: elemental computation, nonconscious cognition, nature as computer

Introduction

Pervasive, high-powered digital information gathering and processing has played a significant role in constituting the 'whole Earth' as an object of thought and practice. Coming shortly after the launch of the first satellite, the International Geophysical Year (IGY) of 1957-8 – a collaborative endeavour involving scientists from 67 nations – is often taken as a turning point in the technologically-mediated sensing of our planet (Gabrys 2016: 1-3). Not only did Sputnik and subsequent space voyages initiate an 'overview' perspective on the Earth, but a whole raft of projects utilising new technologies from spectroscopes and cosmic ray recorders through to mainframe computers produced vast amounts of information about earth and cosmic processes (Lövbrand et al. 2009).

Along with new insights into ice, earthquakes, volcanic activity, geomagnetism, and solar flares, research under the IGY umbrella gave rise to the observations expressed in the Keeling Curve, the graph showing steadily increasing atmospheric CO_2 concentration that became an icon of anthropogenic climate change (Howe 2014: 20-11; Everts 2016). In a more general sense, political scientist Eva Lövbrand and her colleagues argue (2009), IGY-generated geophysical and biogeochemical data opened the way to both viewing the Earth as a single integrated system and to conceiving of cumulative human activity as having come to be significant part of this system. There is, however, a twist to this story. In coming to an understanding of the oneness and unity of the Earth, researchers came to recognise the planet's multiplicity and dividedness: its capacity to reorganize its component parts, from time to time, into a radically different operating state (Clark and Szerszynski 2021: 23-7).

Without this inherent non-self-sameness of the Earth, it would not be possible for certain kinds of human activity to push global climate and other physical systems into a new state or regime. But the planet's self-differentiating tendencies are much more than a threat. Like other forms of life, humans become who they are by responding to the challenges raised by this changeability and by taking advantage of the opportunities opened up by processes of self-ordering that occur at every spatial and temporal scale in the planetary body (ibid.: 9, 93-99).

In this chapter, we ask what digital mediation looks like when we conceive of it as an expression of the multiplicity and diversity that inheres in the Earth. In other words, rather than simply asking how digital communication and data processing shapes the way we apprehend and relate to our dynamic planet, we are interested in what advanced technological mediation looks like when we conceive of it as a variation on the theme of the Earth's own capacity for self-organization and self-transformation.

This raises fundamental questions about the relationship between information and materiality, text and flesh, signs and substance. The fantasy that a new generation of machines 'are all light and clean because they are nothing but signals' was already sent up by Donna Haraway in her renowned *Cyborg Manifesto* (1991: 153), originally published in 1985. Subsequent researchers have detailed the environmental costs of the manufacture, operation and disposal of digital hardware (Parikka 2015; Cubitt 2017). But in the process they have also opened up deeper issues about the relationship of human technological mediation to the operations of the Earth itself – and it is these questions that interest us. If Earth systems are sensitive to human impacts, we ask, what does this say about the way the Earth's own capacity for self-sensing or self-understanding? To put it another way, how might human efforts to develop and deploy information systems in response to planetary change draw upon and extend the material-semiotic capacities of the Earth itself?

We begin with a conceptual framing of the relationship between information and materiality that addresses some of the ways that theorists in different disciplines have opened up the issue of sensing, communicative and cognitive capabilities that extend far beyond human subjects. From there we turn to the deep history or 'archaeology' of human modes of processing information and examine how these developments elaborate upon operations that are part of the dynamism and multiplicity of the Earth itself. This leads us to a consideration of certain 'minority' strands of computation or communicative technology that offer ways of negotiating the material-semiotic properties of Earth systems which differ from those prevalent in today's pervasive digitized infrastructures. Extrapolating from these achievements, and with an eye to earlier lineages that might be revisited and developed in new directions, we speculate about the potential for alternative information technics and practices that might be better suited to the challenges of grappling with a planet undergoing major systemic transformation.

Materiality, information and meaning

At the core of contemporary globalized informatics is the binary signal: a macroscopic state of a component of a digital information system – for example the amount of charge on a capacitor, the alignment of magnetic particles on tape, or the modulations of a beam of light that indicates yes/no, on/off, positive/negative, and nothing more (Negroponte 1995: 14; Piccinini and Scarantino 2011: 7-8). As a sociotechnical system embedded within human societies with their projects and imaginaries, computation involves not just the manipulation of information and binary signals, but also meaning and purpose (Brier 2008). But it is the basic architecture of binary code, massively reproduced and coordinated, that enables different media to converge and exchange contents (Clark 1998). Already by the early nineteenth century, telegraphy based on binary or digital electromagnetic signals had instituted a regime in which data flows vastly outpaced 'analogue' technological media in which information coding remained wedded to various kinds of material substrate – though the latter retained the advantage of much higher informational density or broader bandwidth (Wark 1992) . By the 1930s Alan Turing had postulated that a single, programmable 'universal computing device' could conceivably simulate the workings of any other computing device – in this way anticipating the capacity of digital architectures to merge the capabilities of previously distinct numeric, text, image and sound-processing devices into integrated 'hypermedia' (DeLanda 1991: 129-30; Clark 1998).

Digital computing machines using transistors to do the basic work of switching and amplifying electronic signals were first developed for the military in the early 1950s and became more widely available at the end of the decade (Riordan and Hoddeson 1997: 204, 273-4). An important impetus toward developing a convergent medium of information storage, processing and transmission was the massive amounts of data recorded in incommensurate analogue media over the course of the 1957-8 IGY programme – and the subsequent sense of 'information overload' (Everts 2016). But if making sense of the complexity and dynamism of the Earth was part of the push towards a shared informational architecture, in other ways the digital revolution of the latter twentieth century increasingly engendered the experience of matter and information pulling in different directions.

While some cyberculture enthusiasts gushed about abandoning flesh and substance to enter realities of purely digital fabrication, many other cultural commentators – including environmentalists – voiced concern about the growing detachment of digitally-mediated life from material and embodied existence. As one critic noted of a computerised educational program that enabled children to 'virtually' generate flocks of birds: there are 'no smells or tastes, no winds or bird song, no connection with soil, water, sunlight, warmth, no real ecology' (John Davy, cited by Rifkin 1989: 33-4). It must be stressed that the duality between hefty, resistant matter and weightless, disembodied digitized information – what MIT Media lab founder Nicholas Negroponte described as 'the fundamental difference between atoms and bits' (1995: 4) – has been troubled and unsettled in numerous ways (Clark 1998). The rest of this section sketches out some of these deconstructive moves concerning distinctions amongst matter, information and meaning – though as we later suggest, there are good reasons not to entirely dispense with distinctions between digitized information and other forms of mediation.

One frequent rebuff to the atom-bit dualism (one is tempted to say binary) is to note the increasing implantation of digital processing capabilities in a range of objects and sites: the rendering 'smart' of everything from appliances to clothing, cities to ecosystems (Luke 1997, Gabrys 2016). A related counterargument tracks the multiple ways – from nanotechnology to 3-D printing, that researchers have sought to extend the power of 'universal computing' to the assembling and manipulating of matter (Clark 1998; Birtchnell and Urry 2016). What we want to focus on, however, is *a set of approaches that move beyond the realm of human technics to make a case for informational, hermeneutic and cognitive capacities inhering in the wider physical world*. Social scientists and humanities scholars have grounds to be cautious or downright sceptical when the computer is used as a metaphor for understanding other things, such as the human brain or – in 'pancomputationalism' – the cosmos at large (e.g. Wolfram 2002; Lloyd 2006). Western history has seen many other ground metaphors for nature, not least nature as kingdom, as organism, as machine. However, with care, it is possible to use ideas of computation to understand more-than-human processes. We will explore the idea that computation on human devices can be seen as a riffing on planetary processes – processes that matter under planetary conditions engages in under the right conditions.

Computation and cognition

To clarify what we might mean by talking about computation in non-human nature, we first need to sort out some terms. Literary scholar Katherine Hayles (2014) makes some distinctions along a rough spectrum. At one end are *material processes* that she describes as having no 'intention towards' in themselves – in terms of Aristotle's (1956: V(2)) four causes, these processes involve only his 'material' and 'efficient' causation. At the other end, she places *consciousness*, which for Hayles involves an internal modelling of the self and of the intentional objects of thought, out of which representational practices arises semiotic ‘meaning’, and Aristotle’s ‘final’ causation oriented to purpose.

Roughly in the middle of this spectrum, Hayles uses *nonconscious cognition* to refer to a broad set of processes of modelling, anticipation and other ‘informational tasks’ that supervene on material processes and are in turn sometimes supervened upon by conscious thought. In Hayles’ schema, such processes are not in themselves conscious, and do not involve meaning in the semiotic sense – however they still involve the ‘intention towards’ of final causation. For Hayles, most instances of cognition are of this nonconscious type, and typically occur not in individuals but systems (2014: 201). She assumes that this ‘nonconscious cognition’ is confined to humans, other animals and technical systems – but we will ascribe nonconscious cognition to a wider range of forms of matter.

Computation is an ordered mapping of inputs to outputs. One can meaningfully say that an entity computes in this sense if (i) it is possible to identify phenomena that can serve as the entity’s inputs and outputs, (ii) if the entity behaves in a way that produces an ordered mapping or set of relations between the two, and (iii) if this ordered mapping performs a function for some other entities, assemblages or systems. It is because of this last criterion that, fully understood, just as Claude Shannon’s (1948) quantitative definition of “information” as a measure of the unlikeliness of a signal was criticised for neglecting the dimension of meaning (MacKay 1969; Bateson 1972), so too computation can be said to involve not just the storing, manipulation and transmission of information (for example in the form of digital ‘bits’) but also meaning and purpose. In the case of human-made computers, meaning and purpose is most obviously manifest in the ‘human–computer interaction’ (HCI) that occurs around input and output peripherals, where we might imagine that meaning is added to an essentially meaningless (re)arrangement of 1s and 0s occurring within the devices by the presence of living and sentient human minds (Brier 2008). However, we will suggest that in the case of computation in more-than-human systems, a kind of non-representational meaning is involved, where the 'nonconscious cognitive' powers of matter play a role in wider geophysical processes.

One notable feature of the recent development of human computational technologies is that it has overwhelmingly favoured *digital* computation, which involves the manipulation of discrete elements selected from a finite alphabet. Classical digital computation as inaugurated by Alan Turing is a version of this that takes a particular string or ordered set of digital elements and follows an algorithm or set of rules to produce another string as output. Neural networks also manipulate digital elements but without necessarily having a clearly definable algorithm that they follow to do so (Piccinini and Scarantino 2011: 7-9). Computation in more-than-human systems also lacks sharply defined algorithms but is also typically analogue – involving continuously variable quantities such as mass, velocity, position or magnetic field strength. Indeed, it is out of this world of more-than-human computation involving analogue, continuous physical variables such as electrical charge that designers and fabricators of computers have to fashion and defend the fiction of a digital world of discrete elements, one that is constantly in danger of collapsing into analogue instability.

Nature as computer

> 'If one were to take intricate details of wind and tide and so on, and use them as … "input" to some computer simulating water – what computer would you use, and how would you express the "output"? Water itself: that answers both those questions' (Stafford Beer, in Blohm et al. 1986: 51).

Computer scientist Gary Flake's (1998) *Computational Beauty of Nature* is more than a guide to how to use computation to model the complexity of nonhuman nature; it also makes the case that nonhuman matter *itself* computes, by following simple recurrent rules in a massively parallel way. Flake looks at fractals (including the deterministic ones typically generated by digital computers, but focusing on the stochastic ones created by nonhuman systems such as coastlines, and mountain ranges), chaos (which is deterministic but unpredictable, sensitive to initial conditions), and complex adaptive systems (which learn and become more complex). He identifies three key features that allow us to see these nonlinear phenomena as forms of computation (and thus in Hayles' sense a form of nonconscious cognition). The first feature is *spatial* – large numbers of entities acting in parallel, and interacting with each other (see Szerszynski 2021); the second is *temporal* – like Hayles, Flake emphasised iteration, repetition and recursion; finally, the third feature adds *directionality* in time – adaptation and learning, through the operation of 'filters' and some kind of memory.

However, to understand the complexity and unpredictability of the more-than-human world we need not just ideas of computation but also incomputability. Turing's and Gödel's paradoxes of incomputability involves the recognition that there are calculations and other operations that one might ask a computer to do, but that would never halt, since they can never be completed. Nonlinear natural processes with continuous variables, parallelism and feedback are inherently 'incomputable' in the sense that they cannot be completely modelled or predicted by a digital computer (Flake 1998: 57). However, here Flake invokes another spectrum – not Hayles' spectrum between material processes and conscious thought, but one between computability and incomputability. As Flake puts it, 'nature's most amazing and beautifully complex creations must exist at the juncture between computability and incomputability' (1998: 427).

Flake is here doing a computational version of the observation made by many authors that self-organisation can only take place in a border zone between rigid order and complete chaos (von Foerster 1960; Atlan 1979; Kauffman 1995; Bak 1996). On this spectrum, one end might be described as 'hypermnesic': it exhibits an excess of memory, which systems into all-too predictable and maybe even static, changeless order – like a crystal. The other end of the spectrum is 'hypomnesic': it has a lack of memory, so that all that can occur is chaos (Szerszynski 2019). In the middle is a zone of constant change but underlying structure of function, in which new forms can arise, adapt and even learn (Flake 1998: 426, 429). Natural systems in this middle zone can be seen as storing and transforming *information*, and thereby computing their own dynamic evolution (Shalizi and Crutchfield 2001). But they can also be seen as involving a more-than-human *meaning* and *purpose*, to the extent that the calculative and self-organising powers of material assemblages and systems enable them to play a role in wider planetary processes of self-organisation.

Flake summarises thus: '[n]ature, then, appears to be a hierarchy of computational systems that are forever on the edge between computability and incomputability', in which at each level there is 'structural and functional self-similarity, multiplicity and parallelism, recursion, feedback and self-reference' – and sometimes learning (1998: 429).

Planetary computation and the humanities

Although our exploration of ideas of 'elemental computation' will include both biotic and abiotic matter, a major tributary to humanities thinking about the computational power of planetary matter involved changing ideas about the nature of life. In particular, thinkers across multiple disciplines from the 1950s on displayed an increasing willingness – informed by post-war biology's deciphering of the genetic code – to conceive of biological life as an informatic, semiotic or communication system (Johnson 1993; Clark 2011: 16-19). As philosopher Georges Canguilhem expressed it: '[l]ife has always done – without writing, long before writing even existed – what humans have sought to do with engraving, writing and printing, namely, to transmit messages' (1994: 317). A crucial dimension of this generalised thinking in terms of signs or 'marked elements' was a move away from thinking of information systems primarily in terms of homeostasis and equilibrium towards an appreciation of the way that noise, interference and imperfect translation allowed for the emergence of novelty (Johnson 1993: 142-87; Hayles 1999: 131-59). Later feminist theorists would extend and deepen this deconstruction of the matter–meaning dualism, Haraway speaking generally of the living body as a 'material-semiotic actor' (1988: 595), Vicki Kirby insisting that 'information informs the very matter of (a) body's material constitution' (1997: 3).

But Kirby goes further still, moving beyond the informed flesh of the biological body to 'consider the very real possibility that the body of the world is articulate and uncannily thoughtful' (ibid.: 5). Other thinkers too, travelling along different tangents, have also considered the possibility of forms of calculation or cognition that are neither confined to human intelligence nor to the broader category of organic life. Philosopher Manuel DeLanda muses on observations made by fluvial geomorphologists about the way that rivers sort the pebbles they transport into various sizes. Based on ongoing feedback between the properties of the mobile rocky matter and the dynamic properties of flowing water, DeLanda explains, these '*hydraulic computers*' perform the work of differentiation that generates distinct geological strata (1997: 59-60) .Science fiction writer and speculative thinker Stanislaw Lem suggested that such processes could be harnessed for human purposes. He suggested that a kind of sieving mechanism inserted into a fast-flowing stream carrying variously sized rocks could serve as a selective device, in this way performing computational functions (2013: 260). He went as far as to say that exploiting the computational power of planetary matter in such ways could automate the process of scientific knowledge production. 'We are to invent a device', he wrote, 'that will gather information, generalize it in the same way the scientist does, and present the results of this inquiry to experts' (ibid.: 242).

This brings us back to the idea, roughly contemporaneous with the rise of digitality, that the Earth has a propensity for self-organization and generating its own otherness – raising the question of whether we might conceive of planetary multiplicity not simply as an unfolding of physical forces but as a play of information or even as a kind of self-intelligibility. As well as speculating whether humans might be bringing the earth to self-awareness for the first time, chemist and Gaia theorist James Lovelock also spoke of the much more ancient 'intelligence network' of the living Earth (1987: 46, 148). His Gaia-theory collaborator evolutionary biologist Lynn Margulis was still more emphatic, insisting that 'Gaia, the physiologically regulated Earth, enjoyed proprioceptive global communication long before people evolved' (1998: 142; see Clark 2017). Or as literary theorist Bruce Clarke makes a Gaia-inspired case for a planet-scaled sensing and knowing:

> Some three or so billion years ago, when a critical mass of biotic, biogenic, and abiotic elements fell into a closed loop locking in an emergent level of metabiotic autopoiesis, life and its environment coupled together to produce a primal regime of planetary cognition (2020: 17).

Unsurprisingly, Gaian notions of a sensate or auto-communicative Earth put the emphasis on the planet's coupled living and non-living components. It is worth noting, however, that other approaches to similar questions have been less centred on life. In more recent work Kirby posits an Earth that explores its own possibilities, an astronomical body that 'represents itself to itself' (2011: 41). When she asks: 'is this not a geology, an earthly science?', the implication is that our planet is literally self-investigative: that there is an originary complication of matter and inquiry that is the condition of possibility of the human study of 'geology' (ibid.: 40). Kirby's stance may appear to be an extreme expression of the deconstructive impulse, but in important regards it echoes geologist Victor Baker's earlier championing of a notion of geosemiosis: 'a semiotic that is continuous from the natural world to the thought processes of geological investigators' (1999: 633). Citing pragmatist philosopher C. S. Pierce's assertion that universe 'is perfused with signs', and making connections with continental philosophy, Baker too suggests that human geological inquiry is embedded in a broader planetary and cosmic semiosis – rather than simply imposing understanding on a lumpen, incognisant materiality (ibid.: 637). John Durham Peters (2015) similarly extends the idea of media to include sea, earth, fire and sky – all are media, both in the sense of carrying information and messages and as providing conditions for existence.

In both conceptual and scalar terms, we have journeyed some way from Negroponte's sharp atom/bit divide. Our takeaway point from this breakneck survey is that an Earth infused with multiplicity and self-differentiating potential can also be seen as a planet with its own mediative, computational, cognitive capacities. This in turn, for us, opens up a way of understanding human cognition and its technical supplements less as a split from natural wholeness and more as a kind of tapping into and elaboration upon modes of intelligibility that are bound up in the dynamic materiality of the Earth. In the following section, we look at ways in which a range of information-rich human practices and technics can be construed in relation to the planetary affordances they build upon.

Archaeologies of elemental computation

Until relatively recently weaving was assumed to be a Neolithic technology, a craft invented by sedentary people who had domesticated plants and animals. Then, in the 1990s, archaeologists working at the Dolni Věstonice and Pavlov sites in today's Czech Republic excavated fragments of fired clay that bore impressions of cloth so tightly knit that it could only been produced on a loom – a discovery that pushed weaving back into the domain of semi-nomadic peoples living in the midst of a late-Pleistocene glacial epoch some 26,000-30,000 years ago (Vandiver et al. 1989).

Like the cordage, knot-tying, sewing and basketry that preceded it, spinning and weaving takes advantage of a structure-forming process found throughout in the organic world – the dynamic equilibrium that arises out of two or more spirals with contrary forces coming together (Ingold 2013: 121). Weaving textiles – a systematic operation in which fibres are transversally threaded over and under each other on frame – takes the structural logic of twisting and tangling to a new level. Like basket-making, weaving requires detailed premeditation. In this regard, for cultural theorist Sadie Plant, weaving on the loom is the predecessor of all subsequent automated machinery: '(t)he program, the image, the process, and the product: these are all the softwares of the loom (1997: 189, see also 60-9). Just as pixelated images will reiterate much of the logic of images patterned into textile, so too for Plant, in a more general sense, is the incipient 'programming' the precursor of the textile manufacturing machines that we central to the industrial revolution: flying shuttles, spinning jennies, water frames, spinning mules and power looms (ibid.: 63-5).

Though distinguished by the pronounced feminist slant she brings to the field, Plant is far from alone in her excavation of modern media. Alongside and sometimes in conversation with earlier deeply historical accounts of numeracy and literacy (McLuhan 1964; Ong 1982), there is a well-established body of work exploring the idea that ostensibly 'new' media or informational technologies actually have deep, layered histories. While Friedrich Kittler (1999) blazed unfamiliar trails between the gramophone and early computing, fellow 'media archaeologist' Siegfried Zielinski (2006) tracked still more obscure philosophically, aesthetically and even mystically infused precursors of contemporary audio-visual media as far back as the ancient world. Explicitly engaging with the Anthropocene and other famings of global environmental crisis, Jussi Parikka (2015) gives media archaeology a much more literal focus, both by showing how different media leave physical traces in geological Earth and by probing the ways that different elements and materials lend their affordances to the development of informatic technologies.

In a similar vein to Parikka, this section of our chapter probes 'different ways of mobilizing the earth into and as media' (ibid.: 26). From the fabric arts of the late Pleistocene that may well have gifted us with precursive programming, we turn now to the origins of literacy and numeracy in the burgeoning agrarian civilizations of the mid-Holocene. Much has been said about the invention of writing and numerical calculation in relation to the logistical demands of increasingly complex, hierarchical grain-fed social formations. What especially interests us are approaches that focus on the intimate relationship between materials involved in early notational practices and the gradual abstraction of alphanumeric systems. In the context of the Fertile Crescent, Archaeologist Denise Schmandt-Besserat (2014; 2010) draws attention to the formative role of record-keeping tokens deposited inside and later impressed upon small clay envelopes. By around 5000 years ago, she observes, the impressions themselves were doing the representational work. Schmandt-Besserat proposes that it was the tangibility of the objects in question, together with the definitive plasticity of clay that made it possible to visualize and 'grasp' signs, and to enable them to seem malleable or manipulable (2014: 762-4; 2010; see also Clark 2020).

It is also worth remembering that 'calculus' is the Latin word for pebble, and that 'abacus' is thought to derive from *abq*, a Semitic word for sand. The earliest known human calculating devices involved tracing symbols in a tray of dust or fine sand, or placing pebbles on an arrangement of lines or grooves (Heffelfinger and Flom 2004; see also Ifrah 2001). In a more general sense, we should consider just how crucial working with clay, mud, water and variously size rocks in the construction and provisioning of the riverine urban centres, and we need to keep in mind the vital connections between technics of timekeeping, geometry and mathematics and demands of sediment-dependent social life (Wittfogel 1957: 29-30; Clark 2021). If, as material culture theorist Lambros Malafouris sums up, 'the intelligent use of clay' was critical for the embodied and cognitive shift to literacy and numeracy (2010: 40), we might also say that the intelligent collaboration with sedimentary computational processes – thereby allowing the channelling, collection, apportioning and setting to work of sediment – was the condition of possibility of ancient floodplain civilization.

While the twists and tangles of the organic world that inspired fabric arts can be viewed as a natural self-ordering process, in the case of river-borne sediment this ordering is arguably of another level. As we saw earlier, fluvial geomorphologists and their more speculative commentators have posited that the selective transportation of variously-sized particulate matter by flowing water functions as a selective or even basic computational mechanism. So in this sense, we might consider how the intelligent social manipulation of water, sediment, stones and clay – the underpinning of sedimentary civilizations – can be seen as elaboration upon some the planet's own sorting, probing, calculating and self-organizing capacities (Clark 2020; 2021).

Building on the work of Plant, Parikka, Zielinski and fellow informatic 'archaeologists', it might be possible to reconstruct the late 20th century binary-coded 'universal computing device' out of all its constituent mobilizations of natural and human ordering processes. Along with making use of the self-referential signifying systems that emerged from the play of clay and inscriptive devices, this would include the repurposing of recursive shuttling and switching mechanisms of generations of weaving machines, the use of wheels and cogs ultimately derived from ancient fibre-twisting spindles, utilization of silicate-rich semi-conductive compounds that elaborates upon both naturally occurring glass and the 5-6000 year tradition of artisanal glassmaking, and the processes of copper patterning on microchips that inherits Bronze age metalwork techniques of inlaying silver and gold (see Clark 2018; Plant 1997: 60-9; Templeton 2015).

Conclusion

What general conclusions can we draw from this brief investigation of the idea that digital computation is merely an instance of a far wider planetary phenomenon? Firstly, rather than understanding computation and mediation solely as a human-centred, technological, intentional process – one that has become central in the contemporary understanding of Earth-system processes – we also need to be attentive to the self-ordering, computational, cognitive, communicative and investigative powers of matter itself. Human negotiation with nonhuman materiality is fraught, challenging and perpetually open to mis-re-cognition, in this regard, precisely because the wider world is itself sensing, probing, calculating. Secondly, far from computation necessarily involving a progressive disembedding of human calculating, signifying and communicative capacities from any material substrate, what comes into relief is the profound importance of collective engagement with the stuff of the world in the shaping of informatic media. In this regard, Schmandt-Besserat and Malafouris's elegant paradox that sensorially-rich, hands-on engagement with clay paved the way to the abstraction of number and text is anticipated by pioneering media theorist Marshall McLuhan's point that 'number is an extension and separation of our most intimate and interrelating activity, our sense of touch' (1964: 105). Stanislaw Lem's ideas of using matter's self-organising powers to automate the production, testing and dissemination of scientific hypotheses in a cybernetic 'information farming' may have been a proposal largely designed to provoke. Nevertheless, such speculations and provocations serve to remind us that digitized infrastructures, for all their unquestionable power and velocity, are not the only option for dealing with the informational complexities of planetary matter – just as fossil-fuelled heat engines are not the only way of moving and shaping physical mass.

As media archaeologies help us to see, the development of modern information technologies has taken particular pathways, but in the process other possibilities have been bypassed, marginalized or extinguished. When most of us are so immersed in and reliant upon global digital networks, it can be difficult to imagine what course these other options might have taken and what forms they might yet take. One small step in this direction, we have been suggesting, is not only to acknowledge that our socio-material practices are also informational engagements, but to re-cognise that many of these negotiations are familiar, widespread, mundane. It is here, in the often rather ordinary sites where our own intermittently conscious cognition tangles with the non-conscious cognition of the wider world, that we might look for traces of a more gritty, textured and colourful supplement to the information systems to which we have become accustomed. Although it would likely involve some relinquishing of the speed and raw processing power of the dominant digital regime, we speculate that more-than-digital informatic architectures could play a part helping us to respond – skilfully, generously and receptively – to a planet that is in the throes of rapid systemic change.

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References

Aristotle (1956) *Metaphysics*, tr. John Warrington, London: Dent.

Atlan, Henri (1979) *Entre le Cristal et la Fumée: Essai sur l'Organisation du Vivant*, Paris: Éditions du Seuil.

Bak, Per (1996) *How Nature Works: The Science of Self-Organized Criticality*, New York: Copernicus.

Baker, Victor R. (1999) 'Geosemiosis,' *Geological Society of America Bulletin*, 111(5), pp. 633-45. https://doi.org/10.1130/0016-7606(1999)111<0633:G>2.3.CO;2

Bateson, Gregory (1972) *Steps to an Ecology of Mind: Collected Essays in Anthropology, Psychiatry, Evolution, and Epistemology*, New York: Ballantine.

Birtchnell, Thomas and John Urry (2016) *A New Industrial Future? 3D Printing and the Reconfiguring of Production, Distribution, and Consumption*, London: Routledge.

Blohm, Hans, Stafford Beer and David Suzuki (1986) *Pebbles to Computers: The Thread*, Toronto: Oxford University Press.

Brier, Søren (2008) *Cybersemiotics: Why Information Is Not Enough!*, Toronto: University of Toronto Press.

Canguilhem, Georges (1994) *A Vital Rationalist: Selected Writings from Georges Canguilhem*, tr. Arthur Goldhammer, New York: Zone Books.

Clark, Nigel (1998) 'Materializing informatics: from data processing to molecular engineering,' *Information, Communication & Society*, 1(1), pp. 70-90. https://doi.org/10.1080/13691189809358954

Clark, Nigel (2011) *Inhuman Nature: Sociable Life on a Dynamic Planet*, London: Sage.

Clark, Nigel (2017) 'PyroGaia: planetary fire as force and signification,' *Ctrl-Z: New Media Philosophy*, 7. http://www.ctrl-z.net.au/articles/issue-7/clark-pyrogaia/

Clark, Nigel (2018) 'Bare life on molten rock,' *SubStance*, 47(2), pp. 8-22. https://www.muse.jhu.edu/article/701283

Clark, Nigel (2020) '(Un)Earthing civilization: Holocene climate crisis, city-state origins and the birth of writing,' *Humanities*, 9(1). https://doi.org/10.3390/h9010001

Clark, Nigel (2021) 'Planetary cities: fluid rock foundations of civilization,' *Theory, Culture & Society*. https://doi.org/10.1177/02632764211030986

Clark, Nigel and Bronislaw Szerszynski (2021) *Planetary Social Thought: The Anthropocene Challenge to the Social Sciences*, Cambridge: Polity.

Clarke, Bruce (2020) *Gaian Systems: Lynn Margulis, Neocybernetics, and the End of the Anthropocene*, Minneapolis: University of Minnesota Press.

Cubitt, Sean (2017) *Finite Media: Environmental Implications of Digital Technologies*, Durham: Duke University Press.

DeLanda, Manuel (1991) *War in the Age of Intelligent Machines*, New York: Zone Books.

DeLanda, Manuel (1997) *A Thousand Years of Nonlinear History*, New York: Zone Books.

Everts, Sarah (2016) 'Information overload,' *Distillations*, <https://www.sciencehistory.org/distillations/information-overload>, accessed 31 August 2021.

Flake, Gary William (1998) *The Computational Beauty of Nature: Computer Explorations of Fractals, Chaos, Complex Systems, and Adaptation*, Cambridge, MA: MIT Press.

Gabrys, Jennifer (2016) *Program Earth: Environmental Sensing Technology and the Making of a Computational Planet*, Minneapolis: University of Minnesota Press.

Haraway, Donna (1988) 'Situated knowledges: the science question in feminism and the privilege of partial perspective,' *Feminist Studies*, 14(3), pp. 575-99. https://doi.org/10.2307/3178066

Haraway, Donna (1991) 'A Cyborg Manifesto,' in *Simians, Cyborgs and Women: The Reinvention of Nature*, London: Routledge, pp. 149-81.

Hayles, Katherine (1999) *How We Became Posthuman: Virtual Bodies in Cybernetics, Literature, and Informatics*, Chicago: University of Chicago Press.

Hayles, N. Katherine (2014) 'Cognition everywhere: the rise of the cognitive nonconscious and the costs of consciousness,' *New Literary History*, 45(2), pp. 199-220. http://www.jstor.org/stable/24542553

Heffelfinger, Totton and Gary Flom (2004) 'The bead unbaffled,' *Abacus: Mystery of the Bead*, <http://totton.idirect.com/abacus/pages.htm>, accessed 31 August 2021.

Howe, Joshua P. (2014) *Behind the Curve: Science and the Politics of Global Warming*, Seattle: University of Washington Press.

Ifrah, Georges (2001) *The Universal History of Computing: From the Abacus to the Quantum Computer*, tr. E.F. Harding, New York: John Wiley.

Ingold, Tim (2013) *Making: Anthropology, Archaeology, Art and Architecture*, London: Routledge.

Johnson, Christopher (1993) *System and Writing in the Philosophy of Jacques Derrida*, Cambridge: Cambridge University Press.

Kauffman, Stuart A. (1995) *At Home in the Universe: The Search for Laws of Self-Organization and Complexity*, New York: Oxford University Press.

Kirby, Vicki (1997) *Telling Flesh: The Substance of the Corporeal*, London: Routledge.

Kirby, Vicki (2011) *Quantum Anthropologies: Life at Large*, Durham NC: Duke University Press.

Kittler, Friedrich A. (1999) *Gramophone, Film, Typewriter*, Stanford, CA: Stanford University Press.

Lem, Stanisław (2013) *Summa Technologiae*, tr. Joanna Zylinska, Minneapolis: University of Minnesota Press.

Lloyd, Seth (2006) *Programming the Universe: A Quantum Computer Scientist Takes on the Cosmos*, New York: Knopf.

Lövbrand, Eva, Johannes Stripple and Bo Wiman (2009) 'Earth system governmentality: reflections on science in the Anthropocene,' *Global Environmental Change*, 19(1), pp. 7-13. http://www.sciencedirect.com/science/article/pii/S0959378008000939

Lovelock, James E. (1987) *Gaia: A New Look at Life on Earth*, Oxford: Oxford University Press.

MacKay, Donald M. (1969) *Information, Mechanism and Meaning*, Cambridge, MA: MIT Press.

Malafouris, Lambros (2010) 'Grasping the concept of number: how did the sapient mind move beyond approximation?,' in *The Archaeology of Measurement: Comprehending Heaven, Earth and Time* *in Ancient Societies*, ed. Iain Morley and Colin Renfrew, Cambridge: Cambridge University Press, pp. 35-42.

Margulis, Lynn (1998) *The Symbiotic Planet: A New Look at Evolution*, London: Weidenfeld & Nicolson.

McLuhan, Marshall (1964) *Understanding Media: The Extensions of Man*, New York: McGraw-Hill.

Negroponte, Nicholas (1995) *Being Digital*, New York: Knopf.

Ong, Walter J. (1982) *Orality and Literacy: The Technologizing of the World*, London: Methuen.

Parikka, Jussi (2015) *A Geology of Media*, Minneapolis: University of Minnesota Press.

Peters, John Durham (2015) *The Marvelous Clouds: Toward a Philosophy of Elemental Media*, Chicago: The University of Chicago Press.

Piccinini, Gualtiero and Andrea Scarantino (2011) 'Information processing, computation, and cognition,' *Journal of Biological Physics*, 37(1), pp. 1-38. https://pubmed.ncbi.nlm.nih.gov/22210958
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3006465/

Plant, Sadie (1997) *Zeroes + Ones: Digital Women + the New Technoculture*, New York: Doubleday.

Rifkin, Jeremy (1989) *Time Wars: The Primary Conflict in Human History*, 1st Touchstone edition, New York: Simon & Schuster.

Riordan, Michael and Lillian Hoddeson (1997) *Crystal Fire: The Birth of the Information Age*, New York: Norton.

Schmandt-Besserat, Denise (2010) 'The token system of the ancient Near East: its role in counting, writing, the economy and cognition,' in *The Archaeology of Measurement: Comprehending Heaven, Earth and Time in Ancient Societies*, ed. Iain Morley and Colin Renfrew, Cambridge: Cambridge University Press, pp. 27-34.

Schmandt-Besserat, Denise (2014) 'Writing, Evolution of,' in *International Encyclopedia of the Social & Behavioral Sciences*, ed. James D. Wright, second edition,Oxford: Elsevier, pp. 761-6.

Shalizi, Cosma Rohilla and James P. Crutchfield (2001) 'Computational mechanics: pattern and prediction, structure and simplicity,' *Journal of Statistical Physics*, 104(3), pp. 817-79. https://doi.org/10.1023/A:1010388907793

Shannon, Claude E. (1948) 'A mathematical theory of communication,' *Bell System Technical Journal*, 27, pp. 379-423 & 623-56. https://doi.org/10.1002/j.1538-7305.1948.tb00917.x

Szerszynski, Bronislaw (2019) 'How the Earth remembers and forgets,' in *Political Geology: Active Stratigraphies and the Making of Life*, ed. Adam Bobbette and Amy Donovan, London: Palgrave Macmillan, pp. 219-36.

Szerszynski, Bronislaw (2021) 'Colloidal social theory: thinking about material animacy and sociality beyond solids and fluids,' *Theory, Culture & Society*. https://doi.org/10.1177/02632764211030989

Templeton, Graham (2015) 'What is silicon, and why are computer chips made from it?,' *Extreme Tech*, <https://www.extremetech.com/extreme/208501-what-is-silicon-and-why-are-computer-chips-made-from-it>, accessed 31 August 2021.

Vandiver, Pamela B., Olga Soffer, Bohuslav Klima and Jiři Svoboda (1989) 'The origins of ceramic technology at Dolni Věstonice, Czechoslovakia,' *Science* 246(4933), pp. 1002-8. http://dx.doi.org/10.1126/science.246.4933.1002

von Foerster, Heinz (1960) 'On self-organizing systems and their environments,' in *Self-Organizing Systems*, ed. M. C. Yovits and Scott Cameron, New York: Pergamon Press, pp. ix, 322 p.

Wark, McKenzie (1992) 'Autonomy and antipodality in the global village,' in *Cultural Diversity in the Global Village: The Third international Symposium on Electronic Art*, ed. Alessio Cavallaro, Ross Harley, Linda Wallace, and McKenzie Wark, Adelaide: Australian Network for Art and Technology, pp. 99-104.

Wittfogel, Karl A. (1957) *Oriental Despotism; a Comparative Study of Total Power*, New Haven: Yale University Press.

Wolfram, Stephen (2002) *A New Kind of Science*, Champaign, IL: Wolfram Media.

Zielinski, Siegfried (2006) *Deep Time of the Media: Toward an Archaeology of Hearing and Seeing by Technical Means*, Cambridge, MA: MIT Press.