Technological Forecasting & Social Change xxx (2010) xxx–xxx

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

Types of technology

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ARTICLE INFO

Article history:
Received 29 November 2009
Received in revised form 24 January 2010
Accepted 25 January 2010
Available online xxxx

Keywords:
Technology
Evolution
Animal
Human
Tool
Machine
Networks
Technological systems
Stigmergy

ABSTRACT

Technology is a concept rife with confusion. Here, I argue that technologies can be distinguished as a combination of type of producer and an idealized artefact life history. Using this definition, a number of technologies are identified. The first technology historically, in the Protostomes, was the production of individual or family dwellings. Next came objects such as spider webs for trapping prey. Stigmergy followed, with the social insects, as a collective endeavour to construct a mega-structure using simple rules of accretion. Some birds and primates began to make tools, or simple technological objects whose function is closely related to their form. Humans are distinguished by their ability to make machines. Traditional technology took place once people voluntarily organised into groups with specialised knowledge to produce more complex objects and structures. Monumental objects like ceremonial pyramids came with the command economies of the early agrarian societies, which also resulted in a new category of artefact, the network. Finally, with modern civilizations came ad hoc accretion, or population-level adding-on, to make truly complex technological systems. Developing a theoretical framework within which artefacts, production processes and ways of interacting with them are identified should help the study of technology to become more scientific.

1. Introduction

Many historians suggest that technology is the driving force in history [1–6]. This claim has become so prevalent that it's recognized as a doctrine, called ‘technological determinism’ [7]. Technological superiority is what allows certain groups to conquer or subjugate others, and so expand their domain of influence [8–11].

Technology is also what separates us from every other creature on Earth. After all, the best chimpanzees can do on this front is to use small stones to break nuts open on large stones [12], whereas we build skyscrapers and rocket to the moon. Indeed, it seems blindingly obvious if one just looks around a modern city while thinking of the chimpanzee's forest habitat that technology is what separates us from the rest of creation. Technology thus appears to be a central driver of events we care very much about – human evolution and history – yet we have a very poor understanding of how it evolves. To understand the human condition, we must be able to explain how human technology has become increasingly complex, and increasingly central to modern life, while the technology of other species remains mired in a much more primitive state.

However, a problem arises at this point. Historians don't have the conceptual tools to deal with growing complexity — they may compare one civilization to another, but they aren't in the business of explaining how humans differ from other species. They leave that task to archaeologists and paleoanthropologists. But these ‘pre-historians’ don't have a commonly held, widely accepted notion of what technology is either, much less a theory of how it changes, while anthropologists have tended to argue that a variety of different features make humanity unique – ranging from opposing thumbs and bipedality to grammatical language and consciousness – but generally ignore technology.

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0040-1625/$ – see front matter © 2010 Elsevier Inc. All rights reserved.
doi:10.1016/j.techfore.2010.01.008

Thus, we are left with only a commonsense understanding of technology derived from our direct experience of its effects on our everyday lives. This understanding is vague, as reflected by the definitions of technology currently circulating: 'a body of knowledge used to create tools, develop skills, and extract or collect materials' (http://science.education.nih.gov/supplements/nih4/technology/other/glossary.htm); 'the practical application of knowledge especially in a particular area' (Merriam-Webster dictionary); 'a broad concept that deals with a species' usage and knowledge of tools and crafts, and how it affects a species' ability to control and adapt to its environment' (http://en.wikipedia.org/wiki/Technology). It is difficult to know what counts as technology given this heterogeneity — is it a body of knowledge, the application of that knowledge to some domain of action (e.g., arts and crafts), the results of a particular kind of action (e.g., tools), or all of these? [13].

The result of this amorphous conceptualization is that we can only describe changes in technology in the form of historical narratives (e.g., the Industrial Revolution), or imagine alternative worlds and futures not dominated by technology as a moral critique of this force in our lives [14,15]. What we cannot do is predict how technology will change our lives. Science has thus far only been associated with technology at the 'front end' – with innovation, by applying science in engineering – not at the 'back end', when the innovation has an impact on our way of life.

This is unfortunate, especially given the central place of technology in contemporary life. A more scientifically meaningful and empirically fruitful concept of technology would be of great service. The objective of this paper is therefore to provide a better understanding of what kind of phenomenon technology is, and the ways in which technology has changed over evolutionary time.

1.1. A uniformitarian approach

Part of the reason we have only a primitive understanding of technology, I argue, is that human technology has been conceptually separated from similar activities in other species. Human beings are able to produce very complex artefacts, ranging from automobiles to skyscrapers and globe-encircling computer networks. No other species produces such a range of artefacts. Indeed, the incredible gap between what we and our closest relatives, the apes, are capable of producing in this regard causes many to assert that there is no evolutionary continuity along this dimension of life [16,17]. Rather, human technology is something altogether *sui generis* — that is, without a prior history in other animals. Thus, in anthropology textbooks, for example, there is no mention of 'animal architects' [18–20]. This might be thought to be due to the traditional concern (evident in the name of the discipline) with only human phenomena. But such textbooks treat other aspects of non-human primate life-ways as evolutionary foundations for human developments, such as social organisation, brain evolution, life history differences, and reproductive strategies. Then there are the histories of technology, which sometimes dwell briefly on the perceived origin of technology in primitive tool-making by chimpanzees, or with Neanderthal grave-goods, but then swiftly move on to accounts of Greek arches and the Industrial Revolution [21,22]. Even in books explicitly concerned with the evolution of technology, there is no mention of non-human technology [16,23].[1] Current thinking about technology is therefore largely non-uniformitarian: human technology is 'something else'.

Admittedly, the standard story of human technological transformation – which begins with *Homo habilis* ('handy man'), the oldest human genus – is a compelling one. The handaxes and choppers produced by these early hominids seem about as simple a kind of artefact as can be imagined: roundish stones with only minimal modification to make them serve a bit better as cutting implements. The story then continues through the making of complex tools, machines, the advent of science, and ends in the present day with a dizzying array of high-tech gadgets and technological paraphernalia.[2] In this view, the story of human evolution is coincidental with that of how technology has developed [22]. The human-based story also seems to be complete in an evolutionary sense: it begins, as it should, at the simplest possible origin and dramatically ends in contemporary times, with our incredible diversity of complex technological phenomena, grown from this simple seed.

However, there are several important advantages to rethinking the nature of technology such that it links human and non-human artefact production together. First, if human technology did evolve from non-human progenitors, then our picture of the origins and perhaps later evolution of technology could look different. Identifying common features of human and non-human technology might transform our understanding of how aspects of human technology arose. Second, if human and non-human technologies are members of the same category of phenomena, then better theory about technology will come from considering them together, because that theory will then cover its proper domain.

I will argue here in favour of a 'continuity thesis for technology' which suggests that human technology is an evolutionary phenomenon with its roots in the technologies of related species. Further, I will argue that, like other evolutionary phenomena, the evolution of complex artefacts has taken place through a sequence of developments in phylogenetic time. This story will be told in terms of a sequence of steps, arising from mechanisms which are clearly understandable and motivated by selectionist logic [27].

[1] The opposite is not so true: studies of non-human animal technology consider some aspects of how these precedents led to human manifestations. In particular, comparisons are made between the means of production – that is, the presence or absence of specific mental abilities in animals or humans – and resulting artefacts of animals to human constructions [24,25]. For example, animal technologists suggest that many types of trap made by animals have human equivalents, or that the walls of a termitarium are less subject to cracks than human-built mud houses. There are also discussions of how human and animal tool use are systematically different, [26] or how human technological psychology differs from that of animals, with suggestions that humans have a 'naïve' or 'folk' physics which provides a sense of cause–effect relationships that support complex artefact production [24]. However, this literature has not produced a systematic story of how human technology evolved from antecedents in other species.

[2] Note that archaeologists tell the beginning of this story, then pass the torch to the historians of technology to tell what happens after the rise of civilization. So it currently takes two disciplines to tell the story of human technological advance.

I therefore seek to detail here the mechanisms through which technology has evolved new levels of complexity, producing more and more sophisticated artefacts over time. This provides an overall view of the evolution of technology, from its simplest forms in other animals, to contemporary human technology. The end result is both a typology of technologies, and a theoretical approach to how later technologies emerge from earlier ones. Finally, I discuss the implications of this perspective for our understanding of what kind of thing technology is. In fact, we will see that standard historical and archaeological accounts of the evolution of technology (consisting of various Revolutions and Ages, respectively) are not as informative as the types identified here — at least for understanding changes in technology (rather than in society-at-large). At minimum, the story detailed here provides an alternative perspective on a phenomenon that desperately needs additional illumination.

1.2. What is technology?

Our first task is to get a more precise idea of what kind of phenomenon technology is. Some clarification might be had by examining what types of things can be called technological. Wikipedia (http://en.wikipedia.org/wiki/Category:Types_of_technology) lists the following as types of technology: alternative, appropriate, disruptive, domestic, drive by wire, high, industrial, low, micro, and nanomanufacturing. It is very difficult to discern any pattern whatever in these entries. Elsewhere on the internet, however, one can find a wide variety of adjectives applied to the word 'technology' which exhibit more consistency. These terms restrict technology to particular types of artefact (concrete, sensor, lithic, computer display, fuel cell, and mobile phone), function (communication, transportation, printing, and information), production process (bio, industrial, and wind), or context of use (legal, medical, dental, educational, and e-commerce) — but also other desiderata (creative, sustainable, and future).

One thing which unites most of these highly disparate designations is the involvement of artefacts. Even educational technology is concerned with the use of material tools to help students learn [28]. I therefore argue that technology is about interaction with artefacts in particular contexts of engagement [14,29]. This leaves aside various perspectives which argue that forms of social organisation can be technologies [30], or strictly ideological positions (e.g., ethics as a technology) [31]. Restricting technology in this way should go some way toward making the concept useful.

1.3. What's an artefact?

But what then should count as an artefact? Considerable controversy surrounds the question of what distinguishes artefacts from other kinds of things [32–34]. Standard definitions make reference to intentional design and planning [32,33,35,36]. For example, ICE-function theory suggests that an object is an artefact only if an agent plans to use that object in a specific way, based on a prior body of knowledge about that object's ability to play that role — a role which, further, is consistent with the intention of the object's original designer [37].

Certainly, intentional design distinguishes certain classes of objects from natural objects, like rocks, which are not designed. But the standard tactic of making the definition of artefacts depend on intentionality could also be the reason why scholars from various disciplines commonly assert that human technology sets our species apart from the rest of the animal kingdom: we are a species unlike any other because we alone are technological [21,38]. The intentionality criterion implies that humans are the sole technologists, because we alone have such psychological abilities. However, many species of animal manipulate their environments in ways that produce various kinds of objects and structures that resemble their counterparts made by humans (e.g., spider webs, beaver lodges, and bird nests). Further, chimps have been shown to be capable of knapping artefacts equal in complexity to the technology of the first hominids, [39] and birds have demonstrated abilities to forge tools from novel materials in laboratory conditions [40]. These recent demonstrations suggest there is enough overlap between human and non-human technological capacities to indicate that human technological abilities evolved from those of ancestral species prior to the hominids. The origin of technology should then be pushed backward in time, potentially into the early days of the animal kingdom.

One consequence of this approach is that we must develop a broad definition of artefacts that makes no reference to psychology or design. My argument is as follows. Every behavioural act tends to rearrange or perturb the environment in some way, if only through the depletion of a resource, or the depositing of waste. Behaviour can thus reconstruct an animal's niche [41]. In some cases, the consequences of behaviour last, in the form of enduring physical configurations. In some of *these* cases, animals then interact with these configurations in ways which tend to increase their biological fitness. I will call such physical configurations *artefacts* (see Table 1).[3] (In this paper, I place an everyday word in italics the first time I use it in a technical way, and make reference to its definition in Table 1.) Artefacts are thus the result of particular kinds of interactions between an animal and materials which those animals then find useful.

Artefacts must thus have a material form; however, this is not as restrictive a condition as first appears. 'Conceptual technology' such as computer programs and other forms of intellectual capital like books or DVDs are artefacts, but not in an abstract way: they always exist somewhere, as physically embodied (if sometimes symbolic) information [42]. For example, computer programs are

[3] Note that the artefact concept does not include all durable constructions but only those which are produced primarily so that the animal can achieve higher biological fitness through interaction with that construction. For example, porous, aerated soil is a consequence, but not an artefact, of earthworm activity because it is a by-product, not a product, of these animals moving constantly through their substrate. It is also the case that, practically speaking, one species' incidental niche construction can serve as another species' structure (e.g., rats live in human waste-bins; fish live in shipwrecks). However, it is not the evolutionary rationale of such artefacts to serve such functions, so one species is not considered here to build *artefacts* for other species to use (except in symbiotic relationships).

Please cite this article as: R. Aunger, Types of technology, Technol. Forecast. Soc. Change (2010), doi:10.1016/j.techfore.2010.01.008

Table 1
A technological glossary.

Term	Definition	Examples
Technology	A type of relationship between a producer and class of artefact (as defined by the artefact's life history)	Stigmergy, tool-making, modern
Artefact	An enduring material entity resulting from productive behaviour with which animals interact to increase their biological fitness	Bird nest, computer, skyscraper, genetically-engineered food, transportation system
Technological object	An endogenously used artefact	Spider web, hammer, book, money, domesticate
Technological structure	An exogenously used artefact	House, skyscraper
Technological network	A type of structure with group-level functionality composed of two types of artefacts: nodes and links	Road network, electricity grid
Technological system	A type of structure with group-level functionality composed of many kinds of artefacts, including objects and structures	Telecommunications, public transportation, World Wide Web
Tool	A simple technological object which is made	Hammer, spear, wedge
Machine	A technological object whose functionality is due to the interaction of multiple, distinctive parts relative to one another	Pulley, car, computer
Use	A type of interaction with an artefact to achieve enhanced functionality from behaviour without causing the destruction of the artefact	Exogenous: sheltering Endogenous: hammering
Make	A type of production process in which the producer acts with global knowledge of artefact form and/or function	Whittling Moulding Assembling
Exchange	A type of social interaction in which rights of ownership and/or use of an artefact are passed from one individual to another	Giving Receiving
Consumption	A type of interaction in which the artefact is destroyed	Eating
Procedure	A list of well-defined psychological instructions that guides an animal's behaviour through a series of successive states, given some initial stimulus/state, then terminates (i.e., 'IF a, DO b, c, d, …z.')	If detect pheromone trace, then deposit mud-daub [termite]
Programme	A set of linked, hierarchically controlled psychological procedures (i.e., 'IF x: DO b, c, d; ELSE IF y: DO e, f, g.')	Hook-making [crow]
Cognition	An ill-defined, complex set of interlocking programmes	Bow-and-arrow making [human]
Tradition	Production reliant on a socially-acquired and -maintained body of knowledge held by a specialised group	Metallurgy Ceramic production
Hierarchy	Production within a social system in which certain individuals have the power to enforce others to help produce artefacts	Pyramids
Ad hoc accretion	Production within a social system in which individuals or groups contribute to complex artefacts on an ad hoc basis	World Wide Web

sequences of instructions that take up physical space in a memory store, and also use energy to change the active state of electrical circuits in other parts of computational systems.

What cannot be considered artefacts, according to the suggested definition, are purely mental 'objects' like rules, beliefs, or knowledge. Similarly, 'social technologies' – the application of scientific knowledge to the design and management of social organisations [43], are purely conceptual – and hence not artefacts.[4] Luckily these mental constructs often have behavioural consequences which can include interaction with artefacts (e.g., the factories and offices where business takes place), and hence become part of the technological world too.

Some biological organisms can also be considered artefacts. In particular, humans and a variety of social insects have domesticated other species to serve as, or to help make, food. These relationships involve the domesticating species modifying biological structures in the other species in some significant way so that they better serve the desired ends (e.g., lactation in dairy cows, or cellulose processing by the aphids working as slaves for ant colonies). In this sense, domesticates are *made*.

With this distinction in place, we can return to the concept of technology, and be more specific about the nature of this relationship between animals and artefacts. I argue that artefacts have a particular kind of life history which involves a specific sequence of types of interaction between animals and physical materials [45,46].[5] Further, I will use the following abstract model of an artefact's life history:

Preparation ➠ Production ➠ Interaction ➠ Maintenance/repair ➠ Abandonment/disposal

Each phase of this generalized life history is characterised by a different form of interaction between an animal and an artefact. In the preparation phase, the animal interacts with raw material or the idea of the artefact; in the production phase, with the developing artefact; functional interaction with the completed artefact in the interaction phase; with the dysfunctional artefact in

[4] The phrase 'social technology' has a number of uses currently — e.g., to describe computer communication technologies for sharing information (e.g., Facebook) which are not intended here. The idea that social forms can themselves be technologies is also stronger than the suggestion that social organisation helps determine the form of technological objects, as in the 'social constructionist' position [44].

[5] This is different from a 'product life cycle' – e.g., marketable product, maturation and modification, then obsolescence [47] – which is about a type of artefact, not an individual token of the type.

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the repair phase; while interaction ceases in the abandonment phase.[6] Preparation can thus be defined as the means by which animals acquire the knowledge or ability necessary to produce an artefact, together with the means of accumulating the necessary raw materials. Production causes a new artefact to come into being; interaction normally results in animals achieving benefits through artefact-enabled behaviour; maintenance results in the restoration of an artefact's functionality; and abandonment/disposal is the process through which an artefact loses its interest to the animal. This order is sequence dependent: normally, one can't interact with an artefact before it is produced, and typically an artefact doesn't need repair until after it has been used.

While it is useful to distinguish the criteria that mark technology off from other kinds of phenomena as the production of, and interaction with, artefacts, it still does not provide sufficient detail to stimulate specific hypotheses which can be tested in empirical studies on technological phenomena. However, these phenomena can be further divided into types of technology which are potentially 'close enough' to empirical reality to stimulate testable propositions. I define a type of *technology* as a particular combination of type of producer and type of artefact life history. Thus, two technologies are the same type if they share all the qualities which define a technology — in particular, the same producer, production process, and artefact type. Major differences in any of these components should identify a novel type of technology.

In the remainder of this paper, then, I describe the set of distinct technologies which have evolved in animal species. As with any evolutionary phenomenon, technologies have tended to become more complex over time. In the course of discovering how technologies evolved from simple to complex forms, a variety of issues are addressed, including the way in which human technology differs from that of other species. A few empirical hypotheses are also put forward to demonstrate the ability of the perspective developed here to make testable propositions concerning how technologies impact on animal lifestyles.

2. The types of technologies

By looking at the means by which contemporary classes of animals produce and interact with artefacts (as defined here), it becomes possible to identify types of technologies. Artefacts resulting from changes in producers, production or interaction which have arisen during the evolution of animals, and which have therefore defined new types of technology, are identified in Table 2. The rest of this section consists of detailed descriptions of these technologies, and the kinds of animals associated with their first appearance.

2.1. Dwelling production

The earliest animal 'architects' were the Protostomes (roundworms, molluscs, and arthropods), which built simple *structures* (Table 1) to house either themselves or a small family. Perhaps it is not surprising that the oldest artefacts are shelters from the elements. I will call such structures '*dwellings*'. A wide variety of animals construct dwellings, which can take a number of different forms: burrows, nests, cocoons, or lodges. They can also serve a number of purposes, including predator avoidance, thermoregulation, food storage and facilitating social interaction and mating [49,50].

Most dwellings are primarily constructed of environmental materials. Animals from worms, wasps and mole crickets, to crabs and fish, to mammals (mice, moles, and prairie dogs) construct burrows, or structures formed by the removal of substrate, leaving behind a patterned 'hole' or tunnel in which the animal shelters.

A few marine invertebrates and holometabolous insects (i.e., those which undergo metamorphosis, such as moths and butterflies, bees and wasps), build cocoons, a temporary form of dwelling. These dwellings are constructed of materials which are produced by the animal's body. These insects undergo a metamorphosis called pupation, which is a transformation from larval to adult form. Butterfly caterpillars shed their final skin, which hardens to form a chrysalis that protects and hides the insect inside. Moths, bees, wasps and ants secrete silk and then spin these threads into enclosures before turning into pupae. This serves as a protective covering for the pupa during its transformation process — otherwise they would be essentially defenceless against predation during this time [26]. Similarly, birds build a variety of types of nest: cavity or hole nests in the ground or a tree (e.g., woodpeckers and hornbills), open-cup nests (e.g., robins), and domed nests with a constructed roof (e.g., weavers), or as mounds (e.g., the Australian megapod), to protect their offspring during their period of dependency.

Beavers are the only example of mammalian structure-makers prior to Primates. They build extensive dams to reduce water flow in rivers, and complex lodges in the resulting lake. Humans also construct dwellings. Indications about the likely nature of early human artefactual dwellings come from the practices of contemporary African foragers such as the pygmies and bush-men, who build simple domed lattice huts from plant materials. Other kinds of traditional architecture are similar. The yurt of Central Asiatic nomads and Native American teepee are built of a lattice of sticks lashed together and covered with felt or animal skins, respectively [51]. In physical terms, these dwellings resemble bird nests in structure and construction. (Of course, non-traditional human housing, such as can be found in contemporary Western suburbs, can be more complex in structure and composition.)

Dwellings are not actively manipulated, once completed. Instead, the animal treats it as an independent feature of its environment (e.g., a pupa quietly transforms inside its cocoon). Interaction with the resulting structure is therefore a form of what

[6] This approach is similar in some respects to that known as 'chaîne opératoire' [48], which concerns a number of stages of interaction with technological objects – from the acquisition of raw material to production, use and the abandonment of the used object – developed to study the cognitive requirements of tool manufacture by early hominids. I will not discuss the other phases of the life history here for lack of space; they are not critical to the evolution of technology since preparation is usually easily achieved, maintenance/repair simply preserves functionality, while abandonment/disposal is post-functional.

Table 2
The evolution of technology.

Technology	Origin [a]	Producer	Production process	Interaction	Artefact type	Artefact examples
Dwelling production	Protostomes [annelids, molluscs, arthropods] (530 M YBP)	Individual/ mated pair	Procedural	Exogenous use	Structure (dwelling)	Burrow, cocoon, nest, lodge, house
Trap production	Arachnids (350 M YBP)	Individual	Procedural	Endogenous use	Object (trap)	Web-trap
Stigmergy	Social insects (200 M YBP)	Group (colony)	Procedural	Exogenous use	[Mega-] structure	Termitarium, hive, ant nest
Tool-making	Passerines (60 M YBP), esp. Corvids (20 M YBP)/ Primates (25 M YPB)	Individual	Programmed making	Endogenous use	Object (tool)	Hook, stick, hand-axe
Machine-making	Early modern humans (150 K YBP)	Individual	Cognitive making	Exchange, endogenous use	[Complex] object	Bow-and-arrow, pulley
Traditional production	Modern humans (15 K YPB)	Organisation	Traditional making	Exchange, endogenous use, consumption	Object	Ceramic pot, forged sword, coin, plant/animal breed
Political production	Early chiefdoms/state societies (7 K YBP)	Institution	Hierarchical making	Exogenous/ endogenous use	[Mega-] structure, network	Windmill, pyramid, road/irrigation network
Modern production	Modern civilization (500 YBP)	Group (population)	Ad hoc accretion	Exogenous/ endogenous use	Network, system	WWW, power utility

[a] YBP = years before present (approximate dates).

I will call 'exogenous use' (Table 1) — that is, the structure is taken as given, once completed (except for maintenance and repair). That is, *use* does not typically involve significant changes (in particular damage) to the artefact; rather, it is treated by the user as part of its environment. (Contrast *endogenous use*, in which the animal treats the artefact as an extension of its body, wielding it to achieve some goal — as described later.)

All of these structures are built through the often-repeated execution of a small number of behaviours — such as weaving silk, sticks or strands of grass into a lattice-work, or mud or leaves into a wall. Dwellings are also typically considerably larger in size than the animal which builds them (beaver dams can be 120-metre-wide constructions). These factors indicate that dwellings are produced through *accretion* (Table 1), or the gradual addition of material to a growing artefact.

Given the wide range of species which build dwellings, production can range from being almost totally implicit to being heavily reliant on learning. Even among late-appearing mammals, production can be almost exclusively genetic. For example, two related species of deer mice (*Peromyscus polionotus* and *P. maniculatus*) dig burrows: the former, burrows with entrance and exit tunnels; the latter, a simple, single tunnel running to a nesting chamber. In an experiment, twenty generations of each species were reared in cages without an opportunity to dig their species-typical burrows. First generation hybrids dug burrows characteristic of *P. polionotus*. Backcrossing of the hybrids produced burrows with mixed characteristics, indicating that burrow-building is determined by a small number of loci in which *P. polionotus* alleles are dominant [176]. Indeed, all burrow variants in this genus can be described in terms of four general states: no burrowing, infrequent construction of small burrows, frequent construction of large burrows with irregular shapes, and frequent construction of large, regularly shaped burrows. A phylogeny of mice species and their burrows shows that the complex aspects of *P. polionotus* burrows are derived characteristics from simpler ancestral forms [52]. Burrows repeatedly constructed by the same individuals also show a very high degree of similarity, suggesting a lack of learning from experience [52].

Burrows, of course, are simpler to construct than nests or beaver lodges because burrowing can rely more heavily on the constraints of the consistent qualities of the soil superstructure within which they occur, and creating holes in a superstructure is easier than constructing structures in air or water [25]. Cocoons, for example, can be complex structures. The most complex cocoons are probably those produced by caddisflies. In some species (e.g., *Macronema transversum*), the protective structure produced by larvae is a combination shelter, made of sand attached to silk, and secondarily a web-trap — a silk mesh in the middle of a flow of water through the structure. They are built in flowing water, so constantly subject to buffeting and damage; flies can also take over the cocoons of previous owners, and so are evolutionarily adept at repairing these structures, using a variety of strategies (e.g., starting from scratch with new cocoon; extending one part or another of a structure to make it look like it should [53]; cited in [24]).

Nest-building behaviours, on the other hand, must be selected, ordered, and modified to achieve the goal of a functional nest, given the specific features of each nesting site. However, even novice nest-makers reliably produce a reasonable nest of the species' characteristic type without experience or practice. So the degree of cognitive control over behaviour selection and modification must take place within a general context of routine action. Nevertheless, during their development, birds can engage in significant learning through experience to improve their nest-building abilities [54]. For example, the nest-building behaviour of weaverbirds (who build among the most complex nests) is a complex sequential motor pattern that is acquired over the first two years of life [55,56]. This suggests a biologically-determined sensitive period with dependence on learning locally sensible aspects of building procedures. Experiments suggest that weavers can be tricked into a variety of errors by doing damage to a

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growing structure: they tend to repair the structure by producing a whole new part, which may or may not be the right part [57]. Dwelling production can thus take place via a relatively small number of repeated rules, each of which produces a sub-structure, implying that it could be relatively undemanding in cognitive terms.

The same is probably true of other dwelling-producers, such as beavers (who have been less well-studied). They are known to fix holes in dams, which might indicate that they recognize when the functionality of a dam has been compromised, suggesting that they might have global knowledge of dams as an idealized structure [24]. Alternatively, they may simply be responding to the stimulus of water flowing from the back side of their structure by plugging it.

Such constructions only require 'local knowledge'. As I use it here, the word knowledge can refer to individual memory (i.e., the result of learning through experience, stored in an animal's neural system), or, as in the present case, a form of 'genetic memory', based on the experience of many generations, and incorporated in the animal's instinctive behavioural production repertoire. Knowledge is 'local' when it extends only to the immediate context of work, not to the form of the entire, completed artefact. In effect, such animals do not have access, through memory or perception, to a mental blueprint of the whole structure as they build (which would require 'global' knowledge).

Given this, I argue that dwelling production is based on what can be called *procedural* production (Table 1). Procedures are characterised by a number of relatively independent rules; the parameters associated with these rules can be adjusted in response to local conditions. Procedures produce stochastic behavioural sequences that only run forward, and always to the end; they typically do not include instructions for stopping in case of misadventure (e.g., in the face of some damage to their nest, weaver birds do not start again to produce a proper structure if it turns out they have made the wrong choice of wall instead of entrance; rather, they continue to produce that sub-structure until it is complete [57]).

2.2. Trap production

Spiders and a few marine invertebrates were the next group of animals to evolve which engage in technological activity. These animals have the ability to produce mucus or silk, organic materials excreted by special glands in the animal's body. What makes them relevant here is that they then turn these secretions into traps for prey. These webs of silk take a variety of shapes and sizes (spiral orbs, funnels, tubes, sheets, tents).

The artefacts in this category are not structures but *objects* (Table 1). Unlike dwellings, webs are not shelters. Spiders can live much of the time on their webs, but many also have burrows or other places to rest nearby; a web doesn't hide the spider from predators — in fact, they are often more visible while present on the web.

Trap-building technology also differs from dwelling technology in the fact that use of traps is active, not passive. Capturing prey typically requires manipulation and maintenance of the web. For example, orb-spinning spiders keep a leg on the web to detect any stirrings caused by captured prey, and then wrap them in silk to ensure they don't escape. Some spiders (e.g., *Deinopsis*) make a web attached to earth, but then hold it between their legs and throw it over prey to entangle them [26]. The bolas spider (*Mastophora*) makes a replica of a South American bolas (similar to a lasso) with a sticky blob at the end of a long thread. The weighted strand is twirled and thrown directly at a flying insect. Unusually, trapdoor (Ctenizidae) prey on walking, not flying, animals, and so lie in wait underground. However, they still trap prey in their web in the sense that the burrow is lined by web. Similarly, a marine worm (*Praxillura maculata*) uses a mucous net, held between six spokes that radiate around its mouth, to capture tiny prey species suspended in water. A web is also used for a day or two, then eaten (to conserve silk-making resources) and rebuilt, unless it can be mended easily. These aspects make use of webs *endogenous*.

What kinds of mechanisms are required to produce traps? Webs built by some spiders, at least, reflect recent experience. For example, orb-web spiders which had captured more prey in the previous week on the lower half of their web increased the size of this part of their web when constructing new ones [58]. Variation in web characteristics can also be manipulated by neurotoxins, each of which introduces a specific kind of change to the size, spacing of strands or irregularity of shape of the resulting web [59].

This kind of plasticity is consistent with a modelling exercise in which the orb-web construction process has been imitated by a computer programme using genetic algorithms: a small number of very simple rules evolved through reinforcement. Through comparison with real examples, rule parameters (encoded as artificial genes) were tuned to result in different web characteristics that closely resembled their natural counterparts for features such as spiral distances, eccentricities and hub location [60]. These models and experiments are consistent with trap production being procedural in nature. Since these actions also probably reflect only local knowledge, we can further conclude that trap-making is based on accretive production, like dwellings [61].[7] What distinguishes traps from dwellings is thus the nature of artefact usage: dwellings are exogenous elements of the environment, once produced, while traps are actively manipulated to achieve functionality.

2.3. Stigmergy

After the first dwellings and traps were produced, the social insects (e.g., termites, ants, bees, wasps) arose, with an ability to build artefacts that take the form of mega-structures. Typically these structures are lodgings for large colonies of animals (e.g.,

[7] Traps produced by humans (e.g., fish traps) are not produced using this technology because they differ in several respects: they are *made*, not *accreted*; preparation is not instinctual but cognitive; nor are the resulting traps simple objects — typically being multi-part machines [26]. For this reason, human trap-making is considered to be a form of machine technology (discussed later).

Please cite this article as: R. Aunger, Types of technology, Technol. Forecast. Soc. Change (2010), doi:10.1016/j.techfore.2010.01.008

termitaria, colony-nests or hives) which can contain a variety of architectural elements: tunnels, royal apartments, nursery and fungus cultivation chambers. Such structures are constructed as a collective endeavour.

The rules for constructing these mega-structures are behaviourally simple. Construction takes place in many steps, typically with contributions from many animals. Individuals at each step respond to information left in the environment (perhaps by their own prior activity) using a small number of standardized behaviours [24]. For example, termites build their complex mounds through the repeated process of leaving a pheromone at specific locations which require additional modification. A termite coming along senses the pheromone, places a bit of mud in a particular place, say the base of an arch, then perceives the arch's dimensions, proportions and smell, and responds by putting another bit of mud in a different place, and repeats the process again. Alternatively, one termite communicates the structure's design needs to other termites by leaving a chemical message behind on-site, so that another termite coming along can take the next appropriate step in modifying the structure at that point.

This technology is called 'stigmergy' [62]. Stigmergy means any form of indirect communication among a set of possibly concurrent and distributed agents which happens through acts of local modification of the environment and local sensing of the outcomes of these modifications.

Stigmergy differs from previous technologies in being a group-based production process that is nevertheless restricted to the highly independent, localized knowledge of individuals. Control over construction is thus diffused throughout the structure, with the structural form itself playing a significant role. Building is with respect to simple rules of response to specific, localized cues of form, albeit with respect for the ecological context and situation of the structure as well [63]. Stigmergy is thus also an accretive technology. Through collective activity, each step of which is a simple response to the existing situation, the mound rises from the surrounding ground as a self-organising, emergent construction [25].

The ability of insects to build their complex structures from simple, local rules of interaction has been validated through multi-agent computer modelling [64,65]. In such models, control is distributed among individuals; structure-level outcomes and dynamics appear to transcend the behavioural repertoire of individual agents, and interaction rules are simple, involving only localized communication. Nevertheless, the resulting structures are robust, scalable, and adaptive, reproducing features of a three-dimensional discrete lattice, for example (in wasps), without any direct communication between agents.

This mode of building depends heavily on the natural constraints placed on construction by the physical environment (including the structure itself). Termite mound structures such as pillar and arch shape and size are largely determined by logistic and physical constraints, for example [66,67]. In particular, the amount of water in the primary building material, wood-pulp, regulates the duration and frequency of behaviours in a number of wasp castes, as well as the number of wasps belonging to different task groups. These different levels and kinds of activity in turn determine which shape of nest will develop [68]. Thus, different parameter values of a single building rule can cause the kinds of different paper wasp nest shapes actually observed in nature to emerge.

Particular rules have also been discovered to govern underground ant nest construction. For example, workers use soil temperature as an orientation cue to decide where to start digging, and respond to rising and falling soil temperatures by moving to alternative digging places, or by stopping digging, respectively [69]. Further, the amount of soil excavated per unit time increases with soil temperature and moisture content [70]. The well-recognized correlation between nest volume and the number of workers occupying the nest has been modelled as an interaction of two rules: a positive feedback rule in the form of a recruitment process mediated by pheromones (resulting in an initial exponential growth phase), and a negative feedback rule that eventually leads to cessation of building efforts [71].

These rules are essentially invariant (at least within castes) and hence mostly genetic in origin. In terms of our artefact life history, then, the production stage is only implicit from an individual point of view: social insects are born with the knowledge and skills to build their mega-structures thanks to a prior history of natural selection for the ability to respond to particular kinds of cues.

Of course, showing that a structure can be produced via the repeated execution of very simple rules with decentralized control does not mean that animals actually work that way, especially if the animals in question have significant mental resources. Nevertheless, it is more parsimonious to seek an explanation which requires minimal psychological demands. It is also the case that these animals have limited psychological resources: there are only about a million neurons in termite nervous systems, for example [72].

It is the high degree of coordination in eusocial species which makes possible this specialised degree of simplification at the individual level — evidence that these societies exist as 'super-organisms' [73]. It is also for this reason that these mega-structures have functionality at both the individual and group levels. At an individual level, a termitarium, hive or ant nest provides defence from predation, and (in rare cases) mating opportunities. At a group level, a termitarium can perform functions such as regulating temperature and humidity levels inside the structure with air ducts and ventilation shafts, or nurturing their food source (fungal species) [25].

As with trap production, the structures produced in this way typically involve bodily secretions, either as a secondary building material — e.g., termitaria are made from environmental materials held together with saliva; or as the primary one (bee hives are made of wax and saliva, both of which are secretions).[8] Honeybee comb construction is very much like the termite case, where

[8] Coral polyps also excrete calcium-based material that accumulates to create reefs. But this requires no manipulation by these brainless creatures; there is no separate production process, so coral reefs are not technological in nature.

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individual bees secrete wax, mix it with saliva, and then place it on the comb surface in concert with large numbers of other bees. Workers move restlessly over the developing comb, contributing whatever is needed to various parts of the structure, in stigmergic fashion [74]. Damaged cells can be repaired or destroyed and the wax reused elsewhere. Bees also use plant resins ('propolis') to strengthen cells, fill holes or cracks, or to embalm prey carcasses [75].

Once constructed, the artefact is treated as part of the environment; no attempt is made to manipulate it during interaction. While the interactive behaviour is enabled or enhanced by involvement of the artefact, exogenous use typically occurs without significant wear-and-tear on the artefact itself. In this case, offspring, food, and other objects may be stored inside the termitarium, which is used as a defensive or protective retreat from predators.

2.4. Tool-making

Later-evolving animals, primarily birds and primates, produce artefacts which tend to be smaller in size than the animals which produce them, and which are typically manipulated when used for functional purposes. Production is also typically by individuals. These are all qualities characteristic of trap production. However, in the present case, the resulting artefact is a *tool* — i.e., a technological object which is *made* (Table 1). That is, it is likely that the producing animal has a mental representation of the eventual form the artefact should take while producing it, and that the production process itself reflects the intentional nature of that process. Intentional artefact production – as when a human turns a chunk of stone into a statue – depends on global knowledge of artefact form during the production process. It isn't necessary for the animal to be consciously aware of the end-form during production, only that it have available an implicit mental model of the completed artefact. Global knowledge also need not be inside the animal's head — humans rely significantly on symbolic artefacts (e.g., blueprints) to help them *make* complex objects such as buildings. So *making* can depend on informational aids external to the animal, including social learning, other artefacts and situational cues. This allows animals to single-handedly complete the production of an entire artefact.[9]

Tools began to appear about 60 million years ago with the Passerine birds. Birds such as the woodpecker finch and brown-headed nuthatch pull off twigs from a bush or tree or spines from a cactus, and shorten them with their beaks. This behaviour is acquired through trial-and-error practice, without any social learning [76,77]. This simple kind of tool-making could be largely procedural. However, tool-making in corvids and primates (appearing in the evolutionary record between 20 and 25 million years ago) has been extensively studied and is more complex. For example, chimpanzees are known to fashion spears by breaking off a branch, trimming it of twigs, leaves and bark, and then sharpening the tips of the branch with their teeth — a process involving up to five separate manufacturing steps. Then they use these tools to jab at small primates (e.g., lesser bushbabies) inside hollow branches or tree trunks [78].

Preparation for these impressive feats by both primates and birds involves a variety of processes, making production truly complex. These activities depend on an innate disposition to *make* and *use* tools [79], a juvenile sensitive period [40,77], trial-and-error or experience-based learning, [76,80] as well as observation of tool-making or tool-using behaviour by more proficient individuals [81,82]. Indeed, individual tool production processes are probably a combination of all of these mechanisms. For example, twig tool use in hand-reared juvenile crows showed that these animals had a tendency to engage in tool-oriented behaviour (an innate proclivity to explore tools); but also that individuals who had received demonstrations of twig tool use by their human foster parent showed higher levels of handling and insertion of twigs than did their naïve counterparts, and a choice experiment showed that they preferred to handle objects that they had seen being manipulated by their human foster parent. Thus inherited species-typical action patterns, individual learning of procedural knowledge about the sequence of operations required to make a successful tool, cultural transmission of tool-making strategies, and creative problem solving all contribute to the acquisition of tool-oriented behaviour [79,82].

What is new here, compared to earlier technologies, is the use of conspecifics as models for artefact production — that is, social learning. For example, by observing a human model, a chimpanzee named Kanzi learned to flint-knap (i.e., bang flint stones together to form rock flakes sharp enough to cut through the flesh of prey), demonstrating an ability to use a found object (a stone) to make a flake artefact [39].

Of course, once skills have been acquired through some long-term learning process, execution of particular productions can become routinized and stereotyped through habit formation (i.e., it becomes procedural) [83]. Nevertheless, preparation is concerned with the ontogeny of production, and so must refer to the processes whereby animals gain the wherewithal to perform the kind of behaviours necessary to produce a given class of artefact. I will call this *programmatic* production (Table 1), because multi-step object production requires at least the ability to implement multiple subroutines in sequence, and the achievement of interim goals during construction (i.e., a 'chaine operatoire' [48]).

In most cases, *use* of the resulting object is 'endogenous': the artefact is manipulated in some way so that the animal achieves greater returns from behaviour. Thus, crows in labs wield hooks they have *made* to retrieve hard-to-reach food items, while chimps in the wild poke 'termiting sticks' they have *made* into termite mounds to collect the insects inside.

Most species *make* only one kind of tool, but some species *make* 'tool-kits'. For example, chimps *use* different tools for extracting prey from hiding places, for personal hygiene (e.g., wiping away faeces) and for attracting the attention of conspecifics, particularly for mating purposes (e.g., whistling by buzzing a leaf) [84]. Similarly, New Caledonian crows *make* several kinds of

[9] A single termite could build a termitarium, given sufficient time, but each step would still be based only on local knowledge.

tools for a variety of tasks from different kinds of materials, modifying stems and leaves to create hooks and barbs — e.g., for removing insects from crevices [40,85,86]. These different tools can even be *used* to perform a single task: wild chimpanzees in the central African rainforest spontaneously and customarily *use* a particular sequence of two tools to forage for termites — a stout stick to puncture the nest, then a smaller, more slender stick with a frayed end to fish out the insects [87]. Humans can even *make* tools in order to *make* other objects (e.g., axe, hammer, chisel or saw).

There is a large literature on 'tool use' in animals (e.g., [12,40,88–90]). However, this literature relies on a more general definition of tool than has been applied here. I restrict the word 'tool' to artefacts — that is, objects which have been *produced* (in particular, *made*). The dominant current definition of tool use [91], and a recent amendment [92], are purely functional: tool use is considered to supplement or extend the mechanical, sensory or other powers of the animal user; they augment the means of getting things done [93]. These definitions allow actions involving objects which have simply been picked up and wielded to be called 'tool use'. For example, unmodified stones or tree branches being thrown in personal defence, or dropped or slammed onto food items (e.g., eggs or nuts) to make them edible, or use as probes (e.g., sticks plunged into water to determine its depth) all qualify. I would call such behaviour 'object use'.[10]

I believe little is lost by distinguishing object *use* from tool use in this way; both unmodified objects and tools can serve to extend the functionality of action, or mediate the interaction between an animal and its environment. Much is also gained: tools are placed in their proper context as a particular kind of technological product, and a number of odd implications of the standard definition are avoided [92]. For example, dropping a stone on an egg is tool use if the current, more general definition is used, but dropping an egg on a stone is not, because in the latter case the stone 'tool' is not detached from its physical substrate (even though both actions require the same kind of physical movement, at least roughly the same level of cognitive complexity, and reflect the same intention) [94,95].

In the more restricted definition used here, there is no tool *use* which is not preceded by tool *production*. This *production* can be minimal — for example, removing an object, such as a cactus spine, from its physical context, and cutting it to size to create a probe (the actions of a nuthatch). But this minimal condition still considerably reduces the number of species which can be counted as tool *users*, preserving the common-place connection between tool *use* and intelligence (e.g., by excluding mud wasps hammering the ground with stones, archer fish shooting water at prey, and sea gulls dropping stones on food items). Corvids, for example, are highly encephalized compared to other birds [96]. In particular, birds which *use* tools (as defined here — that is, they manipulate probes, hammers, sponges or scoops), have larger brain-to-body ratio and relative size of the neostriatum (one of the areas in the avian telencephalon thought to be equivalent to the mammalian neocortex) than species which engage in object use (i.e., collect dung to attract dung beetle prey closer to home [97], or batter or drop food on substrates or anvils) [95]. The fact that corvids favour the use of particular feet when cutting pandanus leaves [85] also mimics the brain lateralization of complex skills in primates [98,99]. These results confirm the psychological demands associated with tool-making technology.

2.5. Machine-making

The next advance in artefact production was the ability to make *machines*, or complex objects that achieve functionality through the interaction of their various parts with respect to one another (Table 1). For example, humans make bow-and-arrows to bring down large prey at a distance. It is only the interaction between the arrow and the bow which makes this functionality possible. The psychological difficulty is that this requires someone to *make* a bow, when the bow alone has no particular purpose; it only acquires functionality in company with an arrow. The bow is also composed of multiple parts — at minimum the bow itself and the string held at tension between its ends. So *making* a bow is itself a significant investment with no immediate utility.

Machine manufacturers are thus required to separate *making* from *using* (or, to speak more generally, to separate production from interaction) [100]. Non-human animals can *make* a tool as an end-in-itself (i.e. for its ability to increase the user's power over the physical or social environment), but do not *make* one that has only instrumental value. Non-human animals value artefacts for what they can help them do, not for what they might contribute to some other goal.[11] Complex artefact-making requires the ability to reach a goal that is seen as only one step on the way to a more distant objective (e.g., the finished arrow as an interim goal on the way to constructing a more complex weapon). Recursive making requires hierarchically nested behaviour: the ability to invest in a product which is itself only an investment in future production. The result behaviourally is one episode of effort that is then followed by another. Further, the intermediate goal achieved by accomplishment of the first object's production has no intrinsic value. Because it involves second-order *making*, I will call this psychological ability 'second-order instrumentality': it is the ability to *make* an artefact having no intrinsic value, which is useful only as a means to an end. Other species are restricted to two technological abilities: to *produce* an artefact that is then *used*, or to *use* one artefact to acquire another. That is, they exhibit

[10] Thus, some animals wield (non-technological) objects in ways which increase their biological fitness. Hence technology is not the only way to interact with the environment to increase fitness.

[11] Note that it isn't the ability to engage in instrumental behaviour per se which separates us from other animals because artefact production is instrumental behaviour. In humans, it is artefact *use* which can also be instrumental, because *use* can be put to the production of another artefact. Indeed, some artefacts only have utility as a function of their ability to help people make other artefacts (e.g., machine tools).

make–use or *use–use* chains, but not *make–make* chains.[12] Only by engaging in *make–make* chains can we account for the distinctive characteristics of human tool-making: composite tools, and tools *used* to make tools.[13] It is this ability which must have arisen sometime in the human lineage.

Making something that is then set aside probably requires the ability to psychologically represent it as only the first step in a larger plan — that is, to see the object not only as a whole, but also as a part of an even larger object. Such hierarchical representations, or meta-representations, are a quintessential feature of human cognition [101–103]. A meta-representational mind is capable of planning for a considerable number of alternative potential sequences of activity, [104,105] such as the recursive *make–make* chains necessary for making machines. Once it becomes difficult to explicitly code for the rules governing behaviour – that is, to analytically describe the programme behind production – then it is better to call the responsible agent *cognitive* (Table 1).

From this divorce of *making* from *using*, I argue, everything else about human technology follows. The first thing the divorce allowed was the production of complex objects — that is, artefacts (like the pulley or computer) which only achieve functionality through the interaction of multiple parts. No other animal manufactures such *machines*, though humans have been *making* them for perhaps 150,000 years (a hafted spear perhaps being the first compound artefact) [106,107].[14] However, the ability to engage in instrumental *making* had other immediate consequences as well.

2.5.1. Exchange

Making a bow-and-arrow was still personal manufacture: individuals *made* complex objects and *used* the objects they *made*. However, the divorce of *making* from *use* also allowed another innovation, the concept of exchange value: people began to *make* things which they never *used* because others might want to *use* them, and give them something in return for the privilege. A further consequence of the divorce of *making* and *using* was therefore that individuals began to *make* things which they intended to trade, rather than *use* themselves, and (conversely) to *use* things they hadn't *made*, but rather acquired through exchange. Thus, not only was *making* divorced from *use* by one individual, but also makers could be divorced from users. (It is difficult to date this advance as social interactions don't leave obvious physical remains, although evidence for trade networks between groups dates from at least 150,000 years ago in Africa — roughly the same time as machine-making [107,109]).

This constituted a major change in people's relationship with artefacts. One result was the beginning of delayed reciprocity, and later a barter economy for artificially produced goods. No animal besides humans has been shown to exchange artefacts. Animals actively share food and other resources, [110] but not *made* things.[15]

Psychologically, the exchange of artefacts requires a willingness to lose possession of something in which one has invested, and over which one claims ownership, with the rational expectation of getting something of value in return [112]. It represents a new kind of instrumental thinking: *making* for exchange. It may also require an interest in *making* things that have no intrinsic appeal to the maker (i.e., a thing for which they feel no need).[16]

These features probably facilitated the development of artefacts with social functions (although the first such objects evolved prior to machines). Thus far, I have concentrated on artefacts with physical functions (i.e., that extend the ability of animal users to manipulate or extract resources from the physical environment). But artefacts can also have biological, social or cultural functionality. Biological functionality is not usually considered in discussions of technology, but manufactured objects exist which provide essential extensions of our fundamental needs as organisms. For example, genetically engineered foods are organic materials modified by physical artefacts to increase their desirability as foods or ability to survive and grow, while nanotechnological health aids are physical objects which enhance the biological functionality of animal bodies by fighting pathogen intruders or monitoring vital bodily functions from inside.

Human interactions with an artefact are not strictly determined by the inventor's original intention for its proper use [113], nor by the artefact's physical design [44]; artefacts can also serve symbolic or conventional functions. Histories of use within particular communities can lead to artefacts assuming a typically implicit ‘technical identity’ or function that flows in part from its physical nature, but also as a result of some degree of freedom in how they are *used*. Social consensus helps to fix the particular identity of technological objects in particular communities [114]. This social and cultural functionality can be added to artefacts through common recognition of their ability to play a specific role [115]. For example, a coin, once it has been moulded into a particular form, can take on, in some human groups, additional meaning through mutual recognition of its function as a medium for the social exchange of value. A coin is a piece of metal that can perform its function as money only because people generally confer on it a special status. An artefact's physical functionality arises from its intrinsic characteristics as a physical object, whereas role or status-based functions only work through convention [116]. An artefact's role-based functions (what Searle calls ‘observer

[12] An example of a use–use chain can be seen in New Caledonian crows, which can pick up one object, use it to extract a second object from one enclosure, which is then used to obtain a reward from a second enclosure. [101]

[13] According to Mitcham [13], Aristotle was the first to distinguish types of making: cultivating and constructing. Cultivating involves helping nature to produce more perfectly or more abundantly the things it produces ‘naturally’ (e.g., agriculture). Construction involves producing things not found in nature, even in rare instances (e.g., chairs or computers). However, cultivating in the sense of agriculture or genetic engineering requires, as a prerequisite, the constructive making of implements, so I take cultivation to be a particular kind of *use* of artefacts to manipulate organisms, and concentrate on the constructive making of new kinds of artefacts in this account.

[14] Chimpanzees use a stone hammer to crush nuts against a stone anvil, but don't make either the hammer or anvil [12,108].

[15] Primates in experimental conditions will exchange tokens for food [111], but these tokens are made by human experimenters, not the animals themselves, and so cannot properly be said to be their *tools*.

[16] In this context, money can be considered a special kind of object, an intermediate store of value for which a ‘real’ good will eventually be exchanged.

Please cite this article as: R. Aunger, Types of technology, Technol. Forecast. Soc. Change (2010), doi:10.1016/j.techfore.2010.01.008

relative' because they depend on someone seeing the object that way) can be arbitrarily related to its physical form (e.g., corporate logos need have no relationship to products — witness the Nike 'swoosh'), but can also depend on its form. For example, objects can more readily serve as money if they are small, light, durable and hard to imitate (so that the supply of money is relatively constant); similarly, wedding rings should be costly, individualised and hard to fake.

Further, a role-based function can not only be the proper function of an artefact – the function it evolved to perform [117]; it can be the primary one – also the reason that the artefact is produced. Certainly, again, we have the example of money: pieces of metal not *made* because they can be engraved upon, but for social exchange. These functions are real; they change the way in which these objects are *used* — for example, coins get passed around rather more than other bits of metal which do not function as money.

What is not required by a consideration of these social functions is additional or novel types of technology: coins are produced by a physical process which can be described as one of the existing types (e.g., tool-making or collective making, depending on how much institutional support production requires in a given society). Despite their ability to manipulate abstract symbols, computers are physical artefacts made via some form of machine-making technology.

Observer-dependent forms of value are a separate development in technology, evolving throughout the human period and in parallel with other developments. In this process, functionality based on mutual recognition was first invested in non-technological objects. For example, unmodified sea shells were widely used as money in a variety of groups [118], invested with cultural value by social convention; a Californian marketing executive sold natural stones as 'pets' (the 'pet rock' phenomenon of the 1970s). Later, artefacts of various kinds came to have this kind of value, first in the form of signs on the surface of artefacts (painted decorations on pots; carvings on arrow-points), then as symbolic forms on artefact surfaces (coins, cuneiform), and most recently as symbolic functions executed within machines (computers).

2.5.2. The division of labour

Once individuals didn't have to *use* the objects or structures they *made*, and could acquire things from others (including artefacts such as machines), they could specialise in the production of only a few artefacts. In large social groups, this meant that each individual could theoretically make many copies of only one thing, which could then be exchanged with others to obtain the goods necessary for life. The variety of things which could be made in such an economy was much larger than that possible to a personal technology, where the limits of knowledge, time and skill meant only a few different kinds of objects could be made, even in large groups, because each member of the group had to make the entire suite of artefacts for themselves.

A related consequence of the social divorce of *making* and *using* was therefore a division of labour, or specialisation in production. For every other species, the rule had been that you only *make* what you will *use* (for its own functionality), and you only get to *use* what you have *made* (no exchanges). Each animal was an independent creator and user of artefacts. Human technology was no longer personal in this way.

This division of labour made greater economic surpluses possible, as *use* of more specialised, powerful artefacts could extract even greater value from the natural world. As a result, population size could grow. Formal models have established that larger, more densely connected populations are likely to produce faster rates of technological innovation, and are more likely to be able to evolve, and retain, the complex skills and knowledge which support that level of production [119,120]. Thus, there is positive feedback among the division of labour, the production of surpluses, population growth, and technical innovation. The existence of economies of scale in some technologies also helps with a ratcheting up of cumulative technology [121,122].[17] The result is a constantly increasing sophistication and richness of the technological world.

2.6. Traditional production

A natural extension of specialisation by individuals in the production of certain artefacts was for groups of people to specialise in production. Individuals thus began to voluntarily engage in collective activity to produce artefacts. Persons could in this way specialise on a specific task involved in the production of an artefact, such as forming the head of a pin in a pin production process [123]. In effect, the division of labour was no longer restricted to individuals exchanging their different products; now they could take various roles to collaborate on the production of an artefact within an organisation.

Such collaborative *making* is first associated with the 'big men' societies or chiefdoms, social groups organised at a level above the family [124]. These low-level hierarchical societies already showed evidence of specialisation, probably at the level of economically independent families, in the form of potters, masons, weavers, and priests [125]. Household craft production in excess of the household's own subsistence needs allowed households to exchange goods. This beginning of social organisation probably began as a part-time specialisation to supplement the production of everyday goods, and could include agricultural implements, or water and food storage vessels [126]. Later as the market diversified, the production of intermediate products commenced, with specialists in the production and sale of replacement machine parts, raw materials (wood, metal, plastics), or services such as windmills for grinding cereals into flour. Some organisations produce structures (e.g., factories) as part of their production process, but the intended use of their end-product is typically for exchange, so traditional products tend to be objects.

At about the same time (11–12 thousand years ago), plant and animal domestication began to occur in various locales [8,127–130]. Agriculture (the domestication of primary food crops) is a form of traditional production in which the artefact is a special kind of object: a modified plant.

[17] The concept of cumulative technology features in evolutionary economics (e.g., [121,122]) primarily due to its involvement in explaining economic growth. Although this is obviously a related argument, it is beyond my scope to address the links to economics here.

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Domestication relies on biological forces to help shape the end-product, just as physical production processes rely on forces such as gravity or molecular cohesion to help shape physical artefacts. Hence domestication too is a form of traditional production.

Traditional production systems often include mechanisms for ensuring that knowledge of how best to produce traditional objects is maintained by the producing organisation. For example, apprenticeship into a guild or trade ensures the confident transmission of specialised production knowledge from one generation to the next through guided or supervised practice of the novice by a master, typically over a period of years. Nevertheless, aspects of this tradition of knowledge constantly change, selecting over time a modified prototypical artefact. This results in a changing local *style* of physical objects (e.g., ceramics or money), or *breed* of domesticate. The concept of *brand*, used by contemporary commercial organisations, is an explicit recognition of the importance of style to uniquely identity a particular group's product within an artefact category.

Domesticates have a variety of endogenous uses: consumption (in which the object is destroyed through use, typically through incorporation within the user), for their own production of secondary outputs such as wool or cotton, or to perform services such as transportation (e.g., pulling carts) and even assisting with the domestication of other species (e.g. pulling plow). The maintenance phase of a domesticate's life history (i.e., feeding/tending/weeding) is more important than for other objects, as they have metabolic needs, rather than merely decaying.

Over time, voluntary organisation of the means of production took the form of craft guilds, business firms, and then corporations. In all of these cases, a previous division of labour often moved within the organisation; what economists call 'vertical integration' brought other production functions inside the organisation to control costs and reduce uncertainties of supply [131]. For example, in the nineteenth century, the Carnegie Steel company consisted not only of the mills where its steel was manufactured, but also the mines providing its raw materials (iron ore and coal), and the railroad lines that transported these raw materials to the factory [132]. Incorporation of these various processes in turn required innovations in management within the organisation [133]. Making artefact production more efficient through reorganisation thus had social, regulatory and political ramifications. For example, corporations had limited legal obligations in the case of economic failure, which allowed them to take greater risks in innovating new products [134]. Similarly, domestication has been augmented by the techniques of genetic engineering, a recent, more rapid way of selecting domesticates with special features of use to humans by directly manipulating their genetic material.

People have continued to use the objects and structures produced by such an organised technology, but often don't know much about how they were *made*. As technology became more complex, artefacts became hidden behind 'service interfaces' [14]. Artefacts can be *used*, even if nothing is known by the user of how they were *made*, how they work, or how they are connected to other aspects of life (interfaces tend to obscure the nature and cost through which an artefact achieves its virtues). Good artefacts (Borgmann's 'devices') do this by masking their origin and the mechanics of their operation. For example, how a fire heats a dwelling is fairly obvious, but how a central heating system provides heat is more obscure to the typical end-user. The device itself fades into the cognitive background as users seek to take advantage of the power of sophisticated technology without paying the price of knowledge [14].

2.7. Political production

Grouping labour into organisations produced even greater economic surpluses. In some cases, this surplus was captured by a political elite. Certainly, larger, denser populations tend to co-occur with stratification and inequality [135]. This elite could then employ part of this surplus to pay a group (e.g., soldiers) to defend that surplus, and to coerce submission (e.g., through tribute or taxes) from the populace. Social specialisation probably also increased the need for centralized authority to regulate the production and distribution of goods. It may have given rise to intra-societal conflicts as wealth and power were acquired by religious functionaries or secular leaders [136].

Two kinds of command-based economies can be distinguished: chiefdoms extract surpluses based on rank or prestige; state societies extract or create surpluses through institutionalised control [137,138]. In states, power rests with political or religious office, not individual charisma or as a reflection of clan size, as in chiefdoms.

With these novel kinds of social organisation came the appearance of new forms of structures. Early infrastructure projects, including common housing ('long houses') and the megaliths and dolmens which first date from around 10,000 years ago, have only group-level functionality, and so must have been community-level projects. As a result, they can be considered evidence for the existence of command-based construction beginning around this time [139]. For example, the town of Jericho was enclosed by a ditch about 1 m deep and a wall about 4 m high after about 8000 BC. The stones to build the wall were dragged from a riverbed nearly a mile away. Production in such cases obviously involved large groups of people. These feats of transport and construction suggest not only a sizable labour force but also one that was well organised and disciplined. This was the beginning of political production.

Later, with increasingly hierarchical social organisation, came the possibility of socially organised production for symbolic mega-structures (e.g., Stonehenge or the pyramids in Egypt) to glorify the elite, beginning around 5000 YBP (but more commonly around 3000 YBP). This corporate architecture was built to provide a focus for community-based rituals and to support religious or state ideologies (e.g. [140,141]). Thus, unlike the small domestic objects of traditional production, command-based political production typically resulted in very large scale structures of utility only to the community-at-large, and disproportionately to those in charge of production. Obviously, without the ability to command obedience from a large labour force, such artefacts would not have been produced; the primarily symbolic purpose of such structures (rather than a democratic utilitarian one), coupled with great cost (an honest signal of authoritarian power), distinguish this kind of technology from other modes of production. The production of complex mega structures could thus now be undertaken in two ways: via instinct (as in stigmergy), or through

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intentional design — that is, the creation of rational plans for artefact production by some group able to command execution of those plans by others.

Political production is based in institutions rather than organisations. The primary difference between organisations and institutions (at least insofar as technology is concerned) resides in the nature of power use within the group. The organisations behind traditional production can have hierarchical structure (e.g., corporations), but are based on cooperation among the organisation members who share a common mission (e.g., make a profit for organisation members), whereas political production is based on top-down coercive power in which those at the bottom of the institutional pyramid do not cooperate in production, nor benefit from its outputs in the same way as those directing production. These political institutions range in scale from villages to empires.

Lewis Mumford (1967) calls the social systems underpinning such construction 'megamachines' in which a political authority controls a large number of human beings and other 'parts' that can be put to work to build mega-structures, or perform other specialised tasks that require a high degree of organisation, with an expectation of obedience to command. For example, production could commence with an edict from the authority to erect a ceremonial centre in a certain place. Further production could be shunted to authorities who command that the requisite materials (including labour) be collected. These authorities then probably supervised production by (informal) craft organisations working as intermediaries. Interaction with the resulting structure could be limited to a small number of priests, who might simply hold symbolic rituals there [142].

Chiefdom-based societies (e.g., the Inka, or pre-historic Hawaii) are also associated with the appearance of a novel type of artefact: *networks* such as roads and water supply channels [139,143,144]. For example, the Inka chiefdom created a road network that was the most extensive, continuous prehistoric construction in the New World. By extracting both labour and tribute from local politics, Inka chiefs constructed a vast road system that connected centres of power with the most distant corners of the Empire through more than thirty thousand kilometers of road [145].

A variety of domains appear to be conducive to network development: infrastructure (sewers), transportation (roadways and later railways) and communications (telegraph, and later, the Internet and mobile phone networks). Techno-networks have two kinds of parts: nodes and links.[18] In a road network, the nodes are intersections, while the links are roads. For a sewer, the node is a toilet, the link a length of pipe. People interact directly with the nodes of a network, such as sweeping a driveway (road network), switching on a light (electricity grid), flushing a toilet (sewer system), sending an email (Internet), or boarding a train at a station (railway network). Nodes are hence like *objects*, while the links of a network are typically *structures*. Networks achieve functionality through interaction of these parts, each of which is a separately functioning artefact as well. Thus, networks have functionality at two levels. Nodes and links can have some degree of independent functionality — for example, computers as nodes in the Internet can do local information processing, and one road can get you from A to B (but not A to Z).

The first networks were prepared in the same way as other large-scale artefacts: through centralized command processes, and produced by a potentially complex range of organisations and individuals [2,148]. However, for mega-structures, interaction was endogenous: people actively extracted benefits from engagement with road and sanitation networks. In this sense, they were more democratic than the symbolic mega-structures.

2.8. Modern technology

Techno-networks on a scale larger than empires about 500 years ago began to appear, created by continued, uncoordinated market activity [149,150]. These collections of artefacts were linked together through a process like stigmergy in the sense of being distributed, because production was beyond the control of individual political powers. However, the individuals contributing to artefact production in this case were rarely simply responding to cues from the artefact itself about where and when to make their contribution. Networks now began to take shape gradually, through accretion, as the consequence of many independent, sequential activities by multiple agents. The outcomes of many production cycles were linked piecemeal and iteratively to a growing, but functional amalgam. Evo-networks are not made as the consequence of a directive (like State-based networks), but evolve as the progressive consequence of distributed activity. This kind of production process I will call 'ad hoc accretion'.

A final development then took place in the history of technology. Through mutual involvement in the economy, technological products from different categories came to be interconnected: objects, structures or networks were embedded in existing configurations of artefacts to make a *technological system* [151,152]. In systems, heterogeneous artefacts become enveloped in an organisation or 'industry' such as telecommunications. Like networks, systems have aggregate-level functionality as well as functionality at the level of component parts. However, unlike networks, techno-systems are composed of many different kinds of artefacts.

[18] My definition of a techno-network is narrower than that of actor-network theory [146,147]. Actor network theory mixes organisms and artefacts in the same network (i.e., nodes can be people, groups of people, texts or graphical representations). I argue, instead, that two kinds of networks can interact in technological activity: social networks (in which nodes are people, and links social relationships) and artefact networks (in which nodes are artefacts and links production or *use* relations). Actor-network theorists do suggest that the human components can be isolated in a 'sociogram' while the artefactual components are relegated to a 'technogram', but then suggest that the two kinds of 'grams' cannot really be separated analytically because the concepts of nature independent from society is a Modernist fallacy [146]. This division into two networks has the advantage of limiting the kinds of relationships people can have with artefacts, consistent with the fact that people have different sorts of agency than artefacts — a fact which actor network theory tends to ignore [177,178]. I also argue that links in a techno-*network* are mostly copies of one thing (e.g., roads), as are nodes (e.g., intersections), calling highly heterogeneous collections of artefacts *systems* rather than *networks*. This is another dimension along which my definition is more narrow than that of actor-network theory.

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Power generation seems to be a technological domain which has evolved from a network to a system over time. Power generation systems are composed of objects such as transformers and generators, but also include structures such as buildings as components [2]. What makes it a system is the ability of one part of the system to respond adaptively to changes in another. Thus, components will compensate for fluctuations in electricity supplies to maintain a constant voltage at household level. The working and evolution of techno-systems can be supported by their physical and social environments. Thus, educational, judicial and other social systems can be affected by, and affect, a techno-system. For example, engineers need to be trained to build and maintain the power generation techno-system, while public utilities must respond to laws passed by governmental regulatory agencies concerning what they can charge customers.

Techno-systems continue to transform human life. The latest significant example is the evolution of the World Wide Web: what began as a relatively small scientific network of computers has evolved into a global conglomerate knitting many kinds of products together with individuals, industries and institutions of various kinds [153].

Unlike the first stage in technological evolution of techno-networks, the production of techno-networks and techno-systems at this late stage often takes place beyond the control of any organisation, and so is effectively distributed and long-running. Preparation of the individual component to be linked to the network or system is planned; however, quite often, the way in which the component becomes part of the network or system can be ad hoc. Certainly, modern cities exhibit the characteristics of emergent complex systems [154]. For example, individuals can connect their newly-purchased computer to the world-wide network of linked computers, add web-pages to the general pool of information, and then interact actively with other components of that network (e.g., by buying a product from a company website). In this way, the population as a whole can contribute to, and use, the resulting artefact systems.

3. Discussion

The story told here differs significantly from the typical representation of human technological evolution in archaeology, which takes the form of technological 'Ages' such as the so-called 'three age system' (Stone Age, Bronze Age, and Iron Age) [155,156]. In this system, human prehistory is divided into consecutive time periods, named after the material used in the predominant technology of that time. This categorization has many advantages. First, it is evolutionary in the sense that stone tools are assumed to precede bronze ones, and bronze ones those of iron, in a sequence of increasing technological complexity over time. It is also widely accepted, and focuses on artefacts themselves. However, switches from one age to another can be gradual, with long transitions during which two technologies were in parallel use, introducing some difficultly into the task of assigning a society to a particular Age during that time. Other aspects of social organisation or economy are not always closely tied to technology. For example, in Classical Period Mayan society, science was advanced even though tools were still made of stone [157,158]. As a result, it has proved difficult to typologize societies as a whole based on their level of technological sophistication. Most crucially, societies sometimes did not follow the prescribed order of Ages. For example, in sub-Saharan Africa, many societies moved straight from stone tools to iron-working, thus skipping the Bronze Age [159]. The three age system has thus proven difficult to apply fully outside Europe, the area for which it was devised [160,161]. It therefore cannot serve as a universal description of how prehistorical human technologies evolved.

Similar complaints can be made about the categorization of human history into technological Revolutions by standard histories of technology, such as the Urban Revolution, Scientific Revolution, Industrial Revolution, and Electric Revolution [21,148,162]. There is overlap between revolutions, poor definition of a revolution, non-normative sequences, lack of consistency between domains of a society, and regional variation in the rate of progress through revolutions in some societies as well [163,164].

These standard critiques of periodization schemes are not applicable to the type-based scheme set out here, for a number of reasons. First, the scheme doesn't divide history into distinct temporal stages. The typology proposed here is not designed to classify periods of history or stages of social development, but to distinguish the abilities of different species to interact with their environments. This is useful for understanding how technology itself has changed over time, rather than for its ability to illuminate the ways in which societies or cultures change. I don't claim that a species' way of life can be accounted for by reference to its technologies, only that specific technologies first arose within a particular group of animals. It is true that a given species can be identified with a particular suite of technologies, but that is only because species – and technologies – arise at particular points in a phylogeny.

Second, technologies are specifically about ways of producing artefacts. My definition of technology is narrow; it is not meant to characterise a species or society as a whole, only its productive capabilities. I therefore don't assert that a given society exhibits only one kind of technology. In fact, once invented, a particular technology will tend to persist in a group and its descendants. Thus contemporary Western societies can be expected to exhibit a wide variety of technologies. Using the typology developed here, contemporary developed countries can be said to have access to technological systems, networks, structures and objects. This is not sufficient to determine whether it is a modern or post-modern society, which would require additional information about governance, and economic and cultural institutions.

Some scholars might complain that the concepts of *interaction* and *use* are highly impoverished or under-theorized for modern artefacts. Once produced, they become embedded in complex webs of historical, social, cultural and economic factors that influence the nature and meaning of such interactions [165,166] — factors which have not been explicitly discussed here. However, there is an implicit recognition of these complexities in the recognition that human technologies require complex groups to sustain their production, and through the notion of technological systems, which involve a wide variety of artefacts as well as supportive infrastructure and social organisation [167].

It is true that, since the advent of machines at least, the nature of interaction between user and artefact has become more complex than merely a one-way modification by the user of the artefact (e.g., inducing decay). On one hand, users have become

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able to modify objects to suit specific uses (e.g., computer memories can be modified by uploading various kinds of software). It is also true that 'exogenous use' can cover a wide variety of functions. For example, people can *use* the internet to purchase commodities, to communicate with friends, to listen to music, to store data, or to subvert governmental power. On the other hand, some kinds of *use* involve changes in the user's identity (e.g., a tool-user becomes a machinist). This inter-penetration can even be physical (various degrees of cyborgism, from wearing glasses to pacemakers) [146,147]. A separation of user from used is thus not so clear in some cases. It is probably worth calling this kind of endogenous use *transformative*, since it involves transmutations in the nature of the interacting parties.

Such novel developments are possible because human technologies depend on 'second-order instrumental thinking' [100] which makes production recursive: any number of means can be interposed between the initiation of production and its completion in a functional output. As a result, production can become an arbitrarily long process with many intermediate goals, each of which can involve the production of intermediary artefacts, enabling the types of artefacts to proliferate. The result of this novel mental ability, working over time, is the incredibly sophisticated life-world we see around us. Complex mental culture alone is not enough to explain human evolution. It is the co-evolution between people and the increasingly complex things they produce which renders human life-ways so different from those of other species.

4. Empirical Utility

If the perspective developed here is to prove useful, it must be capable of inspiring testable propositions. Here, I demonstrate, in a small way, the kinds of inferences that can be made from the definition of several different types of technology.

First, by defining types of technology in the way I have, I have implicitly made a large number of claims about cognition, use types, and types of artefacts.[19] In the case of some non-human technologies, it is difficult to know exactly what kind of production process is associated with a technology. In fact, there is considerable controversy about the degree of cognitive sophistication required to account for non-human technology, with some scholars opting for relatively parsimonious mechanisms [61,64,79], while others are more generous in their interpretation of such technology-producing behaviour [24,85]. The problem is that a sequence of constructive behaviours can have several kinds of immediate causes: it can be 'pre-programmed' through a long history of evolutionary selection for stereotypical forms of behaviour (often given stable environmental conditions); or it can reflect learned skills, acquired either through trial-and-error, or by modelling the behaviour of other, more expert animals; or it can be due to 'insight': goal-seeking behaviour based on an internal representation of the desired form of the finished artefact. Indeed, a given technological behaviour can be the result of all three of these kinds of causes simultaneously. Taking a macro-evolutionary perspective should help to resolve these issues.

I have described the production of each type of technology in terms of the least complex psychological mechanisms that can account for the behaviours associated with production by the original group of animals engaging in that kind of technology. In doing so, I made use of a particular vocabulary – computational terms – for these production processes because they are commonly understood, and reasonable stand-ins for actual mechanisms in a wide range of species. Such terminology should facilitate comparative claims about the degrees of psychological sophistication underlying these types of artefact production, since they are abstracted from actual implementations (which are likely to be species-specific). Thus, for example, I have implicitly claimed that no artefact network can be produced by anything less than an institution composed of agents with cognitive-level minds.

Of course, once an adaptation has evolved, it tends to persist, so it is always possible that an earlier form of production is used in the execution of a later kind of technology. For example, some behaviours performed as part of tool-making are likely to be stimulus-response. Of course, the reverse can also happen: later developments in production methods can be applied to earlier forms of technology. Thus, humans can use cognitive means of producing dwellings, for example. I emphasize that claims made here about psychological mechanisms are restricted to the minimal kinds of psychological sophistication necessary to account for an animal's technology, not its general capabilities.

I can also make predictions about features of technologies which have not yet been discussed, because they are not intrinsic to their definition, but which follow from those features (i.e., are corollaries). For example, the dynamics of change in the outputs of the various human technologies should be quite different. Tool-making and machine-making produce objects that may require some degree of skill acquired through social learning. But they began, at least, as technologies which could be executed by individuals, and hence could be idiosyncratic (i.e., exhibit a relatively low degree of heritability over time). Traditional production involves the iterative making of generations of objects by groups with specialised knowledge; this should result in an evolving local style of physical artefact or breed of domesticate. Political production results in single structures (e.g., pyramids), while in modern production, the technological output (a network or system) is never complete; instead the complex artefactual unit just

[19] My typology of artefacts can be compared to that developed by Mumford [168] (as systematized and elaborated by Mitcham [13]), which includes the following categories: clothes (body-covering artefacts), utensils (domestic artefacts like pots and dishes), apparatus (kilns, vats), utilities (roads, electric power networks), tools (instruments manipulated manually to transform the material world), machines (tools that don't require human energy inputs but do require human direction to perform work), and automata (machines that require neither energy nor direction from humans). Obviously, the categories in this list are not mutually exclusive, since automata are a type of machine and machines are a type of tool, while the other categories (clothes, utensils, apparatus and utilities) might all be said to be 'non-tools' because they are have immediate utility, rather than being used instrumentally to transform the world. For these reasons, I feel the Mumford–Mitcham typology is not as parsimonious nor useful as the one suggested here.

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keeps changing in size and configuration. Almost by definition then, the specific configuration of a network or system produced using modern means will be unique.

The artefacts resulting from any form of production thus can exhibit a degree of heritability (i.e., qualities of style). That is, later productions will tend to resemble earlier ones produced by the same producer, or in the same locale in terms of form and the specifics of function. I predict that the degree of heritability a technology will exhibit depends to a large extent on the type of information used to regulate the production process. In early-arising forms of technology, this information is largely genetic; it causes the formation of relatively simple neural systems which use procedural rules or programmes to induce constructive behaviours. Later, when production takes place through groups, such rules can be augmented by social learning, which results in copying the artefactual forms of others. In the case of political production, political power itself can be inherited, with the result that an offspring's monuments can resemble the parent's. However this is not a necessary feature, as they can also be quite idiosyncratic in form or function, reflecting the whim of an individual tyrant (e.g., Egyptian Sphinx, Great Wall of China). Networks of various kinds can also resemble one another (e.g., European and African mobile phone networks use similar components), and certainly the elements of networks and systems often exhibit a high degree, due to standardization to ensure their interoperability (e.g., all rails in a railway network have to be of the same gauge) of commonality.

One pattern to have emerged from this investigation is that non-human technology is different from that of human animals in a fundamental way: it does not accumulate [18,169]. Each major development in technology prior to humans required a new species to arise with a special adaptation to facilitate performance of the behaviour underlying its novel outputs. Further, each pre-human technology is specialised in large degree to the production of a particular type of artefact — e.g., a trap, dwelling or tool. Human technological advances, on the other hand, are largely additive: later technologies build on the capabilities which earlier technologies made possible. Thus, technological systems are built from the components of simpler technologies, including craft products and contributions to networks. I argue that this is due to the fundamental psychological attribute of human technology: the ability to separate production from interaction, [100] which makes both production and interaction recursive. This should allow further elaboration, and hence the evolution of additional types of technology in humans.

A primary virtue of the current approach is that it is able to help resolve some long-standing debates in the study of technology. For example, one of the most enduring debates concerns techno-determinism — the suggestion that the infiltration of devices into the fabric of human society is increasingly pervasive, irresistible (i.e., beyond the control of individuals or societies) and transformative (i.e., causes irreversible reorganisation in the societies subject to such forces) [7,170,171]. The perspective provided here suggests that the 'balance of power' between people and their technologies is likely to be ever-changing and multifarious (hence the inability to resolve the debate). The 'dehumanization' associated by some critics with modern technology [1,4] appears to result from the fact that our ancestors contributed, generation by generation, to the built environment; we now live within its bounds, by which we are both empowered and constrained (e.g., the mechanization and institutionalisation of some kinds of work). At the same time, we continue to interact actively with many kinds of objects from toothbrushes to computer game consoles. So we 'dominate' some aspects of the techno-niche by dictating how techno-objects are used, but treat other parts (e.g., networks and systems) as largely exogenous to our activity. The nature of our technological relationships thus changes as we move from one category of artefact to another, largely depending on whether *use* is endogenous or exogenous (i.e., whether the artefact remains 'untouched' by our interaction with it), the phenomenological qualities of *use* (e.g., is the artefact much larger than the user?) and the degree of separation between production and *use* (i.e., whether our knowledge of production process is local, global or effectively non-existent). Hence, the prediction here is that interacting exogenously with a technology, which appears phenomenologically 'large', the production of which we have made little contribution to, or the process of which we know little, should be seen as largely determined by the technology, not by the user. Identifying types of technology provides more nuanced answers to this question about power.

In other cases, the perspective developed here does not provide a definitive answer a priori. How do the various technologies interact amongst themselves in contemporary human societies? Modern market economies include machine-making, collaborative production, network building and system building happening side-by-side. One prediction is that they are still distinguishable modes which operate independently in separate corners of our society. For example, individuals can be doing machine-making, business firms collaborative production, while political production occurs as a result of governmental dicta.

On the other hand, little remains in modern societies of 'cottage industry' or hand- and craft-made artefact production, though these modes remain important in developing countries, where tool-making (e.g., pottery-making and other crafts) and dwelling production (e.g., family-based shelter-making from raw materials) continue. Is this because such technologies are now embedded within over-arching organisations in modern economies?

Another example: Can one technology morph into another? It would appear so: what began as an independent network – the Internet – has now become centrally embedded in the international economy, and so is part of a global system, the World Wide Web. However, the means by which this happened requires investigation. Did institutions grow around, and migrate to, the computer-based network to make it central to the world economy and society, or did the network infiltrate existing organisations (e.g., businesses) to change the way they accomplished existing functions (e.g., product sales)? Answers to how the various kinds of technologies identified here interdigitate and evolve in the ecology of particular human societies await further study. But at least we now have more precise ways of asking such questions.[20]

[20] This approach to understanding technologies is value neutral. My goal is to build an account of how technologies evolve, not to find ways to bring them under control so as to maximize human well-being (c.f. [14,15,173]).

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5. Conclusion

This paper has shown that it is possible to find a common thread running through the things which should count as technology: they all involve a relationship between a kind of artefact and the way in which some species of animal interacts with that artefact through its life history. Identifying this commonality gives us an increased degree of understanding of technological phenomena.

One reason that the notion of technology is currently so vague – and hence not conducive to the development of a science concerning how technology impacts on agents – is that it covers a wildly heterogeneous set of phenomena which are better understood as consisting of different types of technologies. I argue that all these technologies have a common origin in the invertebrates. From this origin, a number of different, novel technologies have arisen. Generally speaking, some aspect of these new technologies has become more complex with time. In particular, I have proposed that there are multiple, incremental differences in the mental capabilities and in the resulting types of artefacts which have been produced through evolutionary history. Typically, these later-evolving types of technology are associated with more complex causal processes.

In telling this story, specific definitions have been developed for artefacts, technologies, types of artefact production processes and ways of interacting with them, all of which work within an explanatory system that helps us understand how technology has evolved from early beginnings long ago. This should help scholars of technology to better identify hypotheses about how particular types of technologies worked in specific periods or places — as suggested here with a number of examples.

Techno-environments are now the context within which we humans function. We produce everything from small, isolated objects to a complex market of objects and structures, to networked copies of artefacts, to socially organised production, to pervasive and heterogeneous technological systems. A major consequence of this rapid evolution of technology has been that humans have, in the space of a few thousand years, gone from being *makers* to *users* of most of the artefacts they interact with. (Indeed, a major problem for contemporary design is to minimize the knowledge needed for *use*). Since technology has become cumulative, each generation inherits an increasingly customized environment from the previous generation. Indeed, contemporary Western humans live within environments that are largely the product of prior human activity: cities composed of mega-structures such as skyscrapers, techno-networks such as road and electricity grids, and techno-systems like the World Wide Web. Any individual's activities consist of the small-scale modification of this inherited environment, which has to be taken as a technological 'given', as part of the extrinsic, ineluctable context of an individual's activity. By now, this inheritance has become one of a modified planet. We have tailored the environment to such an extent that we influence 'natural' parameters such as atmospheric temperature on a global scale. Thus, for humans, the modern life-way involves a massively reconstructed niche as the environmental context within which all activity (technological or not) takes place. All human behaviour is therefore intrinsically technological, rather than just involving occasional interaction with a made object, as is the case for other animals [46].

The human life-way is likely to continue to involve significant interaction with techno-systems. Certainly, the long-term trend is for technologies to extract greater power from the environment over time [106]. For example, artefacts have become more powerful as parts of techno-systems, because they gain a new level of functionality through interaction amongst themselves. Whether particular interactions with artefacts will be empowering or debilitating for a given individual is hard to say. In one vision of the future, artefacts will come to be increasingly embedded within the bodies of organisms, literally empowering people's physical and mental capacities by making us 'transhuman' [173]. Less rosy futures predict humanity will be overwhelmed by increasingly powerful technologies to which we will be enslaved [174]. It isn't presently clear what factors are crucial in determining whether humans will continue to control the increasingly powerful artefacts they produce [7,175]. What is clear is that it is unlikely that the technological juggernaut is going to stop. Through continued transformations, it is likely that yet other types of technology will arise in future.

Acknowledgements

Many thanks to David Christian, Val Curtis, Tim Earle, Mike Hansell, Gaby Judah, Bela Nagy, John Odling-Smee, Beth Preston, Jochen Runde, Michael Schiffer, Fred Spiers and several anonymous reviewers for reading earlier versions and thereby adding considerable value to this paper. Thanks as well to Clive Lawson for the invitation to think about these issues in the first place.

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Please cite this article as: R. Aunger, Types of technology, Technol. Forecast. Soc. Change (2010), doi:10.1016/j.techfore.2010.01.008