December 2019
No. 2019-010-e

Journal of Integrated Creative Studies

The evolution of human information-processing

Sander van der Leeuw
Arizona State University and Santa Fe Institute
Email: vanderle@asu.edu

Abstract. This paper is the result of an encounter between two complementary approaches in two different fields: the physical evolution of living beings from monocellular organisms to full-grown animals and humans on the one hand, as developed by Murase, and the evolution of information processing among humans, as developed by van der Leeuw, on the other. Out of that encounter came a speculative vision that this might be the starting point for developing a powerful approach to integrate biological and social science approaches, such as is now required if one is to tackle the fundamental issues of the Anthropocene. That approach is based on a processual perspective on signal processing as an endogenous-exogenous exchange that is fundamental for all organisms. It is still very much a work in progress, of which only the bare bones are becoming visible. In this paper, I focus on the approach to human information processing involved.

Keywords: self-nonself, signal processing, Anthropocene, societal evolution, socio-environmental integration

Introduction

In the relationship between our human societies and their natural environment the present is characterized by the fact that human societal and technological dynamics are increasingly shaping the natural environment. Hence it is known as the Anthropocene, and involves a major transition in humans' relationship with their natural environment. However, many of the research methods that are applied in the domain of 'sustainability science', which is directed at helping along a profound transition between our current societies' values and approaches to the environment and a sustainable future, pre-date the current situation and are no longer appropriate for improving our understanding of the dynamics involved. Thus, they do not provide the information-based understanding that is necessary for the design of appropriate policies. We must look for ways to arrive at intellectual fusion between, notably, our studies of the dynamics occurring in the domains of biology and society. Maybe, just maybe the following pages offer a pointer in an appropriate direction.

My encounter with the editor of this journal, Masatoshi Murase, has led to discussions that integrate some of my fundamentally Western-based ideas on human information-processing and its role in shaping the co-evolution of human societies' cognition, institutions, economies and environments (see van der Leeuw 2019) with some of his ideas on the evolution of life that are based in Eastern thinking (e.g. Murase 2018). In this paper I will attempt to outline the result of this confrontation for my perspective on the evolution of human information processing.

The core of that encounter is the assertion that all life-forms simultaneously exchange matter, energy and information between and among themselves, and that this exchange has both internal and external components. Murase calls these "self-nonself" exchanges (2018: section 1), in which any cell, organ, organism or being absorbs elements of its environment and, in return impacts on other elements in that environment. The commodities transmitted consist, evidently, of energy, matter and information. The former two of these are responsible for maintaining life, and are subject to the law of conservation, which means that they cannot be shared. They are also the substrates carrying information, which can be shared and as such is responsible for the coherence of ecologies and societies.

During evolution, the ways in which matter, energy and information have been transferred and processed has evolved and describing that evolution might be one way to approach a unified perspective that integrates both the human and the non-human living world, based on elements of both the Eastern and the Western perspectives on living systems. In this paper, grounded in a complex systems approach, I will focus on the evolution of human information processing and how it has shaped human societies of different kinds, from small-scale hunter-gatherer groups to our very complex global society.

What do I understand under "information"?

First, I need to clarify that I am using the concepts of "information" and "information processing" in a much wider sense than is usual in many technical disciplines. An important reason for that is that Shannon's (1948) conception, on which much of the mathematical and information science x treatment of information is based, concerns communication in a closed system, such as across a telephone line. In such a system, the emitter and the receiver are assumed to have the same interpretative capacity, so that coding and decoding are based on the same rules and interpretations.

In living systems that is not necessarily (and in fact rarely) the case. Whereas the bandwidth for communication between monocellular organisms is very narrow, and signal emission and reception therefore lead to highly predictable and invariant reactions, in humans (as we shall see), that bandwidth is very wide, and both signals and interpretations can be very varied, depending on the means, knowledge and insights, as well as the contexts, of the individuals concerned, and of their messaging. To a lesser extent, this seems also to be the case for many animal species, for example. One of the themes of the research I propose (but have not elaborated here) therefore concerns the evolution, among living systems, of the dimensionality of these bandwidths and therefore of the range of signal emissions and interpretations available to different species.

A "Complex Systems" approach?

I also need to clarify what I understand by "the study of complex systems". In essence, in my perspective, all living systems – from monocellular ones to societies of plants, insects, animals or humans are complex because they are part of much wider dynamic contexts. In my mind, all non-human species' dynamics are complex, and their confrontation with – equally complex – human dynamics may lead to "wicked" problems (Churchman 1967). Rather than as a special subject, I define the study of complex systems therefore as a particular approach to the study and understanding of any kind of living phenomena, rather than as an approach that is only applicable to a certain set of phenomena.

In attempting to develop a unified materialistic-holistic systems perspective that could serve as a basis for the integrated study of socio-environmental phenomena at all stages of evolution, it seems that a conceptual model is needed that summarizes evolution in terms of complex system dynamics. Designing such an approach begins with identifying its ultimate drivers. But it should be clear that their dynamics will be instantiated in different ways in different places and different times, among different groups of beings.

The approach that I am using here is one that emphasizes the complexity of all societal and natural dynamics, shifts from the study of the results of processes to that of the dynamics driving them, and from the (*ex post*) search for the origins of observed phenomena (explanations) to the (*ex ante*) search for the emergence of these phenomena, and it describes both trajectories and phenomena in terms of processes rather than entities or states. It concerns open systems, and adopts the tenet of ontological uncertainty – there are at any point in its trajectory a number of potential futures open to the system, and which ones the system chooses is not a priori predictable. The trajectory of the system depends on the interactions between the system and its environment, which in biology is described in terms of niche creation. Many other characteristics of the approach have been mentioned in the literature (Mitchell 2011), and will be referred to where appropriate in the remainder of this paper, but the above serves to distinguish this approach in a first approximation from more traditional, reductionist scientific approaches that are still being practiced.

Prigogine and Nicolis formulate the fundamental shift effectively from a Western perspective as "*From Being to Becoming*" (the title of their 1980 book). Murase (2018) describes the same idea from an Eastern perspective, as: "'Life' should not be an object to be distinguished from an external observer, but the creative circulatory processes linking the subject and the object to construct new dimensions that cannot be predicted or defined in advance". In that context, he refers to authors such as Izutsu (1975), Varela et al. (1991), Atmanspacher and Dalenoort (1994) and Bateson (2002).

All living beings, be they unicellular beings, plants, insects, mammals and human beings, as well as all other life forms, are negentropic systems. They process flows of matter, energy and information, and what distinguishes different life forms are the ways in which they process such signals and the information they carry, and how this configures them in ensembles that can be viewed as systems or networks. Following this lead, the conceptual model I adopt will be to view the interaction of entities with their social and natural environments as a *dissipative flow structure* (Prigogine & Nicolis 1980) that combines outward and inward flows of information, matter and energy. In the process, it dissipates negentropy (van der Leeuw 2007, 2019b).

Cellular signaling

In his 2018 paper, Murase develops a vision of the body of any living beings, including humans, as an inter-cellular society that is derived from a single cell through progressive cell division and differentiation of structure and function. It is, where applicable, composed of dividing cells (such as skin and liver cells) and non-dividing ones, such as nerve and muscle cells.

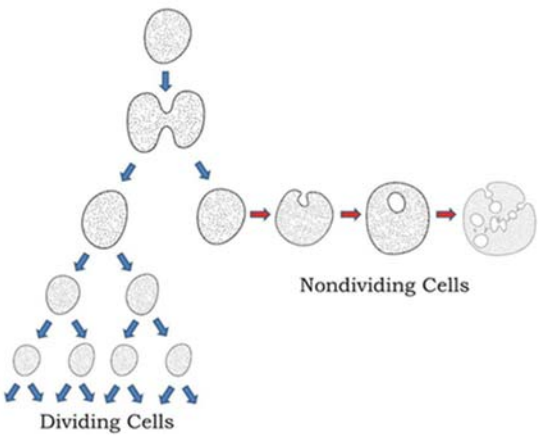

Figure 1: *A body as an intracellular society within an intercellular society. Our body is composed of two different classes of cells: dividing and nondividing cells. Those cells are a clone of a single fertilized cell (shown at the top) subjected to successive cell division and cell differentiation. Although the complex intracellular society is only illustrated in the right panel, any cell has its own intracellular society* (Murase 2018, fig. 1).

Within that inter-cell society, according again to Murase (2018, Springer, Singapore), each cell is itself an intra-cell society with different elements that each have their own function. Neurons, for example, undergo remarkable changes in morphology during early childhood as well as late adulthood in response to environmental stimuli (Doidge, 2015). The plasma membrane not only plays a dynamic role in intracellular signalling (Rothman, 1985), but also undergoes continuous cycles of endocytosis and exocytosis, as illustrated in Figure 2. A small part of the membrane is continually internalized in the process of endocytosis and is conversely added to the cell surface in the process of exocytosis (Dautry-Varsat and Lodish, 1984; Bretscher, 1987). These dynamic cellular processes are responsible for the remarkable adaptability of nerve cells to environmental stimuli, but such dynamic processes are, of course, not determined by immediate gene instructions. Instead, they are driven by the coordinated activity of a complex metabolic network, since metabolic proteins serve as the main machineries of molecular recognition and catalysis and also determine the shape and structure of the cell.

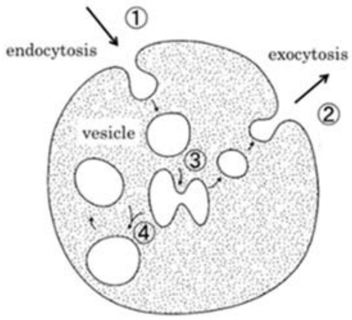

Figure 2: *The dynamic characteristics of a living cell. Four different processes are represented: 1) the uptake of external molecules by endocytosis, 2) the secretion of molecules by exocytosis, 3) the budding of transporting vesicles, and 4) fusion of different vesicles.* (Murase 2018, fig 2.)

Murase thus argues that both individual cells and cell societies continuously integrate matter from outside, and excrete matter that is captured by other cells. The issue that, in this context, needs to be investigated, is *the extent to which, and the manner in which, inclusion and excretion of matter between cells functions as a simple mode of signalling*.

Murase extends this ('endo'-'exo') approach to the next level by creating a model of the interaction between random polymers and "membrane-bound" vesicles, which have their own boundary membranes that can contain micro-environments favourable for certain polymers. In that interaction, then, these micro-environments create the conditions for the interactions between random polymers and vesicles.

Viewing signal and information processing as a basic characteristic of all living beings – and building a model based on that assumption – might provide a unifying perspective that could integrate all living organisms from unicellular ones to humans in one approach. It would, as it were, shift a fractalic approach from phenomena to the processes responsible for them, and would emphasize the build-up of a more and more complex information processing apparatus as fundamental to evolutionary transitions. How could we corroborate or falsify the utility of such a hypothesis? Without attempting, in this paper, to fully answer that question, in the following sections, I am raising some aspects that merit in-depth research.

Resonance and interactions among organisms

If we assume in general terms that energy or matter flows through organisms carry signals that are encapsulated in the exact nature or form of the impulse emitted or received, we can also assume that every organism has an apparatus in place to respond to such signals in ways that are particular to it. That apparatus could be activated by a resonance with the signal received, and the organism would respond with a state change (growth, decline, movement, behavior, etc.). The precise effect the signal would have on the organism in question could be determined by the combination of the nature of the signal and the structure of the signal processing apparatus of the receiving organism.

Every entity (cell, organ or organism) is also embedded in a complex network (an ecology). After reception, the entity interacts with the signals received, and the ways in which it does so impact on the organism itself (generating a reaction, some form of behavior, or a transformation, for example). The resultant state change would, in turn, determine the nature (and the information content) of the signal(s) that organism would emit to other entities in that network.

Fundamental in the interaction between signals and entities is the nature of the resonance between them. If, from an evolutionary perspective, one compares the nature of that interaction for unicellular organisms with the interaction one may observe in more complex organisms, it is notable that for unicellular organisms the range of signals is very limited, and so is the range of reactions by which such organisms can respond to the signals received. More complex organisms, on the other hand, can resonate with a wider range of signals, and can vary their responses, as well as the signals they in turn emit. More complex organisms in effect have a wider bandwidth in receiving, reacting to, and emitting signals. Those differences in bandwidth, at least superficially, seem to be commensurate with the organizational complexity of the different species.

The evolutionary increase in bandwidth

If our approach is to provide a unifying perspective that can integrate all living organisms from unicellular ones to humans in one approach, it must deal with the fact that the signals emitted and processed vary widely among organisms. That requires an additional hypothesis, notably that signal emission and reception are species-specific. In that case one must include a hypothetical driver that is responsible for change in signalling systems and species.

In a very interesting hypothesis, Lynn Margulis (1970, 1981), argues that eukaryotic cells are intimately linked with others in their environment, forming associations of different kinds, in which cells may have different functions and structures. With co-author Bermudes she proposed (1985) symbiotic relationships between organisms of different phyla or kingdoms as the driving force of evolutionary change, and explained genetic variation as occurring mainly through transfer of nuclear information between bacterial cells or viruses and eukaryotic cells in a process they called "*symbiogenesis*".

Their *symbiogenesis* hypothesis is now widely accepted for the formation of organelles, but the proposal that symbiotic relationships explain most genetic variation in more complex living systems is still something of a fringe idea (but see Aanen & Eggleton 2017 on cockroaches and termites, for example). Yet, I will here tentatively adopt this hypothesis and view each individual living entity (cell, organelle, organ or organism) as a symbiosis of a large number of other entities of different degrees of complexity, with different structures and functions. Any entity, at any level of complexity, is in that perspective considered to be a complex (eco-)system in its own right.

Not being a biologist, I will now take the easy way out and, for the time being, jump over the many evolutionary stages of complexity between entities for which this hypothesis would need to be confirmed. Instead, I will try to use the same perspective of endo-exo dynamics for the evolution of human societies, in order to illustrate the evolution of signal processing for societal evolution, the transformations that societies of modern humans (*Homo sapiens sapiens*) and their ancestors have gone through from small, mobile, gatherer-hunter bands to large-scale sedentary agriculture-based societies.

The evolution of human information processing

Looking over the long-term history of human information processing, in contrast with that of most animal species, one remarks that the bandwidth of the information processing involved has increased many orders of magnitude from the earliest humans (*Homo sapiens*) some 2,000,000 years ago to modern ones (*Homo sapiens sapiens*), and that said increase has accelerated in a major way over the last 15,000 to 10,000 years. Many animal species have in recent years shown to be capable of some degree of learning, or even learning how to learn. But only human beings seem to have the capacity to deal with the complexity of information processing that is currently occurring worldwide. That was not always the case. The earliest humans could barely handle more information than Chimpanzees. What has happened?

To gain some better understanding of the growth of human information-processing capacity, I need to first consider some major biological changes. These are summarized in Figures 3 and 4 and Table 1.

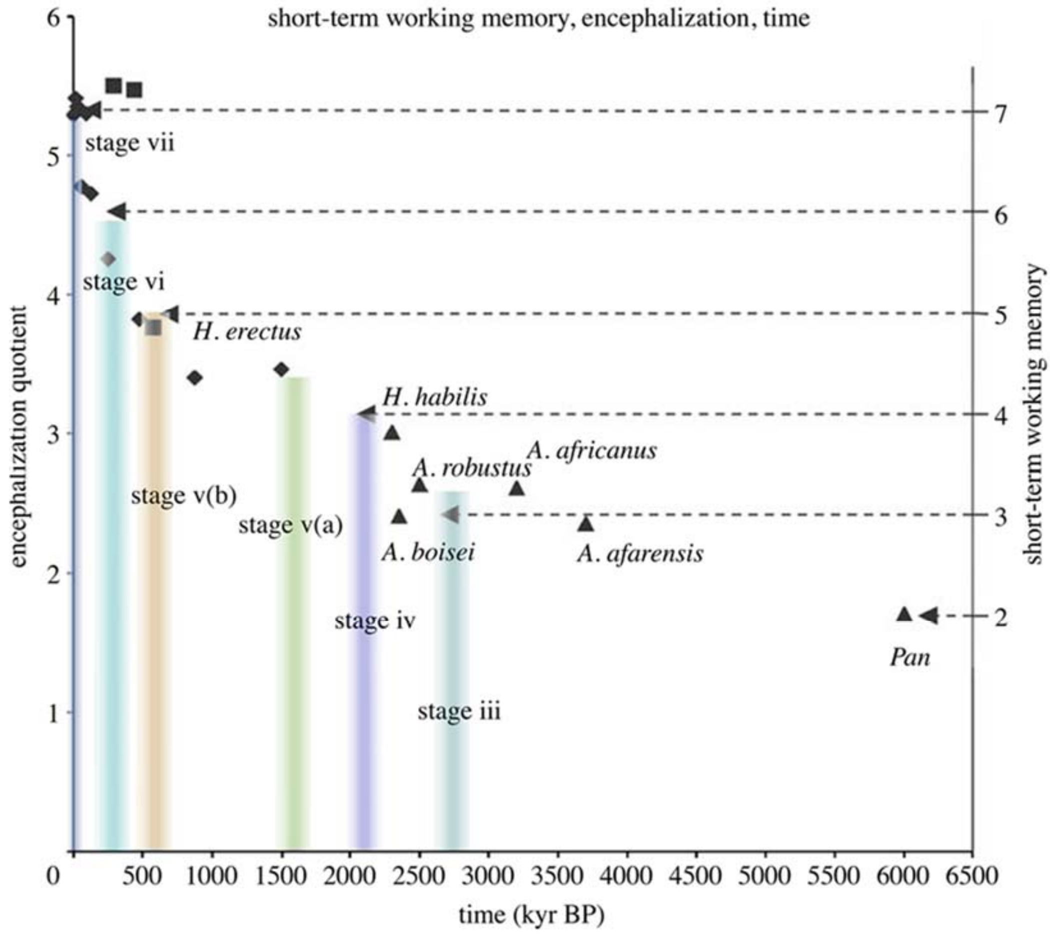

Figure 3: *The encephalization quotient changes over time, indicating that the size of the brain, relative to the size of the overall body increases proportionately. (For more detail about this, see Read & van der Leeuw, 2015).*

Figure 1 summarizes the growth of the brain relative to the growth of the body of human beings. The stages refer to Table 1, which documents the evidence for the growth of the human Short Term Working Memory, the part of our brain that enables us to link in our minds a number of information sources. Over the 2 million + years of hominin evolution, its capacity increases from 3±1 (that of chimpanzees who are able to crack nuts) to somewhere between 7 and 8, which means that human beings can deal with more and more complex challenges. The number 7±2 has been arrived at experimentally: most people can handle 7 information sources, but some cannot, and some can do better than that. One may imagine an STWM of 7 as the capacity of a juggler to hold 7 balls simultaneously in the air, but when an eighth ball is added, loses control.

Table 1: *Relationship between the complexity of technological actions (columns 2-6) and the Short Term Working Memory (STWM, column 8, in red). Column 9 dates the stages of the technological evolution, and column 10 refers to the archaeological name of the stone tools concerned, and in some cases to the place where they were found. (For more detail about this, see Read & van der Leeuw, 2015).*

Sta-ge	Concept	Action	Novelty	Dimensionality	Goal	Mo-de	STWM	Age BP	Example
1	Object attribute	Repetition possible	Functional attributes present; can be enhanced	0	Use object		**1**		
1A	Relation-ship between objects		Using more than one object to fulfil task	0	Combine objects		**2**		
2	Imposed attribute	Repetition possible	Object modified to fulfil task	0	Improve object		**2**	> 2.6 My	Lokalalei I
3	Flaking	Repetition	Deliberate flaking without overall design	0: incident angle < 90º	Shape flakes		**3**	2.6 My	Lokalalei 2C
4	Edge	Iteration: each flake controls the next	*Debitage*: flaking to create an edge on a core	1: line of flakes creates partial boundary	Shape core	1	**4**	2.0 My	Oldowan chopper
5	Closed Curve	Iteration: each flake controls the next	*Debitage*: flaking to create an edge and a surface	2: edges as generative elements of surfaces	Shape biface from edge	2	**4.5**		
5A	Surface	Iteration: each flake controls the next	*Faconnage*: flaking used to make a shape	2: surfaces are intended ele-ments, organ-ized in relation to one another	Shape bi-face from surfaces	2	**5**	500Ky	Biface handaxes
6	Surface	Algorithm: removal of a flake prepares the next	Control over location and angle to form surface	2: Surface of flake brought under control, but shape constraint	Serial production of tools	3	**6**	300 Ky	Levallois
7	Intersec-tion of planes	Recursive application of algorithm	Prismatic blade technology: monotonous process	3: flake remo-val retains core shape – no shape constraint	Serial production of tools	4	**7**	.50 Ky	Blade tech-nologies

The study of stone tool making illustrates part of this process, in a simplified form, in Figure 4. The earliest stone tools are none other than simple pebbles that have been sharpened at one point. This requires an STWM of 3, as both the future tool, and the stone with which it is hit, have to remain at an angle of less than 90º. By implication, the dimensionality of the change effected on the stone is zero. Once a whole series of such flakes is taken off, in a line, the dimensionality of the activity is 1 (a line). As, in the next stage, the line closes upon itself, it leaves in the middle a surface to be taken off, which if course is two-dimensional. The fact that there are instances where the line is flaked first, and the surface taken off later, as well as instances where the reverse happens, indicates that at this point, people became aware of the choice between a one-dimensional approach and a two-dimensional one. Skipping a complex intermediate stage (Levallois), the next line shows that people actually conceived stone-tool making in three dimensions. At that point, the knapper prepared three distinct surfaces, one horizontal one at the top, and two, at right angles, on two sides of the stone, and then chips off blades from one of those two surfaces.

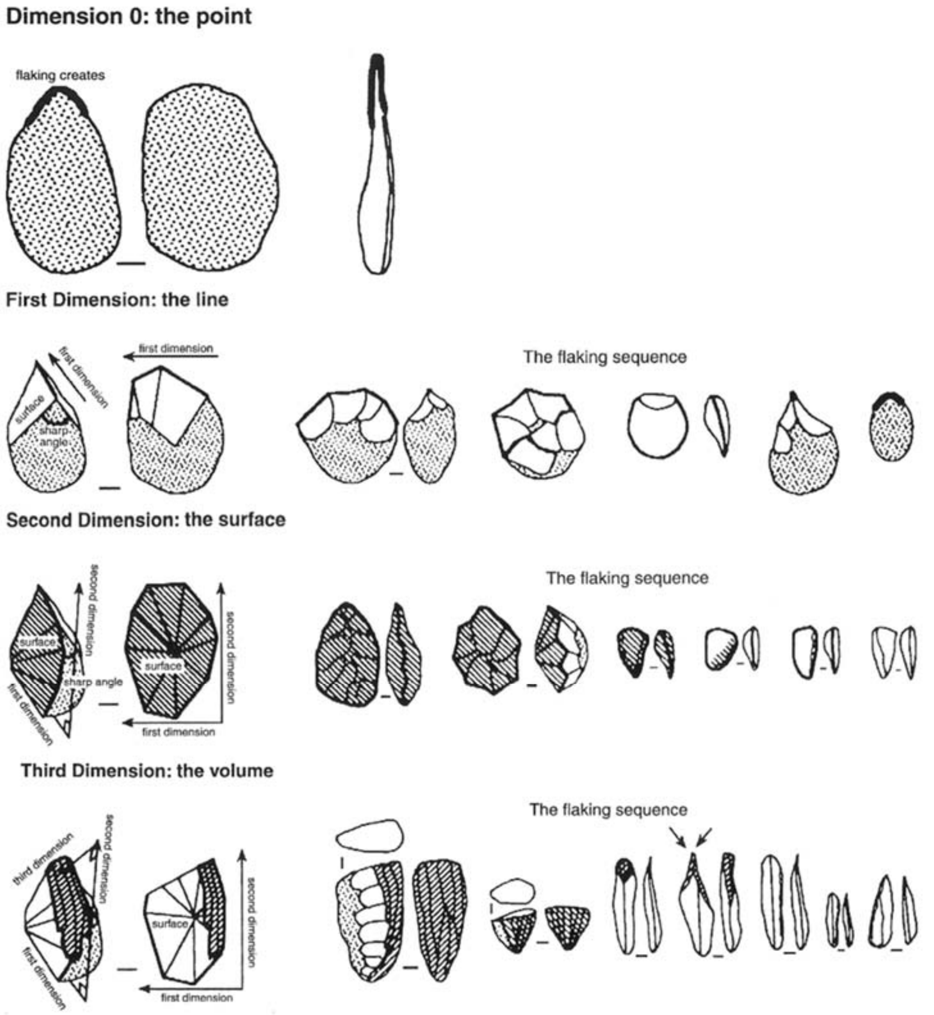

Figure 4: *Over time, humans learn how to distinguish the three dimensions of any stone object, and use that knowledge in the way in which they create tools. (For an explanation, see text below; after van der Leeuw 2000 and Read & van der Leeuw 2015)*

Over time, one can thus follow how the exploitation of what was of course always a three-dimensional object (the stone), led to the conception of that object in three dimensions. The human mind has, as it were, 'bent itself around' the problem of dealing with three-dimensional objects due to the increasing capacity of the Short-Term Working Memory to deal with more and more sources of information.

Very important research by Atsushi Iriki (2019) and his team at the RIKEN Institute in Tokyo, combining functional MRI with learning experiments on Japanese macaques and insights from anthropology and archaeology is beginning to unravel the dynamics behind this long-term evolution, and in particular behind the phase transitions *that have generated* Homo sapiens *and* Homo sapiens sapiens *as an interaction between tool-making and the development of cognitive capacity.* For our purposes this research is most accessibly summarized in a recent presentation that the author made to the *International Convention of Psychological Science*. I will refer to this presentation as needed in my argument below.

A feedback loop drives the evolution of human information-processing capacity

For most of human evolution, as outlined above, the extent to which the realm of ideas could thus be enriched was limited by the biological capabilities of the brain. But somewhere between c. 200,000 and 50,000 years ago, this changed. After that time there is no evidence for a further increase in STWM, yet human beings rapidly enhance their information processing capability, which culminates in the industrial revolution and the explosion of technology to deal with everything, including information processing itself. What might be the driver of that explosion in human information processing capacity?

On the one hand, this is the period of emergence of Neanderthal people (*Homo sapiens sapiens,* 200,000-100,000 BP); on the other, around 50,000 BP the STWM of 7±2 seems to have been reached, and archaeological data seem to indicate that groups of people are collectively processing information. Did the combinatorics associated with an STWM of 7 or 8 offer such a wide range of possibilities and opportunities to process more complex information that it can be the explanation, as Read and I argued in several papers (2009, 2015)? I no longer believe that the solution to this riddle is so simple.

Iriki (2019) invokes the emergence of epigenetic transmission in a wide sense (cultural, technological and social) for this transition, in which an interaction between artefact making, (proto-) language development, and growth in brain size, as well as social learning drive the development of the modern human brain's information processing. Potential other factors may include enabling organizational changes in the brain as a result of variations in diet, as Iriki is currently trying to show between coastal and inland macaques in the Indian Ocean. Another element in the puzzle might be that collective information processing enables dealing with more complex challenges. And yet another factor might be the externalization of information processing through the development of technology.

Whatever the reasons, I will for the moment assume that the dynamic driving the development of the information-processing apparatus after c. 50,000 BP can be represented as is done in Figure 5, below. The loop in the figure links the outside world (the realm of observations) with the cognitive capacity (the realm of ideas) of the brain, or as Iriki (2019) calls them the "outside niche" and the "inside niche" through resonance. Observations in the outside world are interpreted as far as they resonate with existing interpretative schemes, that is as far as they provide information that fits the existing realm of ideas. But because the phenomena in the outside world are more highly multi-dimensional than the interpretive schemes they resonate with, those observations are never completely identical to the relevant parts of the realm of ideas. Any interaction between the outside and the inside niche therefore triggers challenges to the information-processing apparatus in the mind in the form of problems or challenges. Once these are met, they in turn enhance the information-processing capacity of the brain. That enhanced information-processing capacity will be able to resonate with new observations that have not been made before, and the cycle will start anew. The development of the growing information-processing capacity, therefore, depends on an articulation between existing cognitive structures in the brain and the outside world.

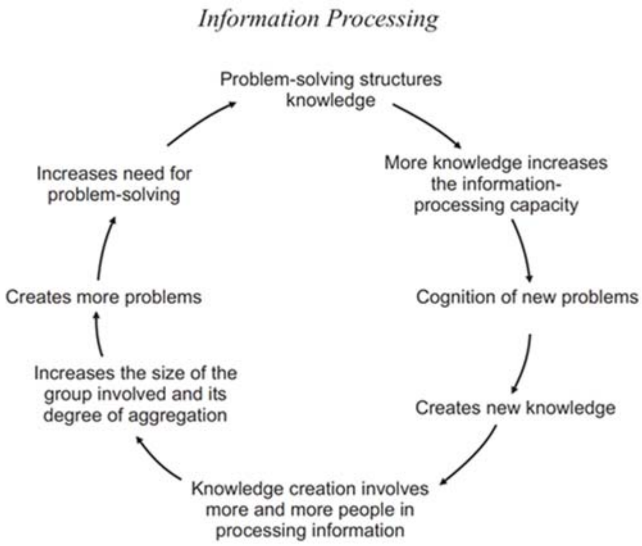

Figure 5: *The information processing loop* (see text below) (after van der Leeuw 2006)

In the absence of a biological constraint to this articulation, the main constraint on the development of human information processing capacity is the development of the inside niche itself, that is the existing information-processing structure. As its growth is stimulated by its interaction with its environment (the outside niche), each group of human beings builds up a way of being (linguistic, social, institutional, technological and environmental) that anthropologists are used to call a 'culture'. It is entirely determined in a path-dependent way by the learning trajectories of such groups that result from observing phenomena, interpreting them and testing the interpretation until it is deemed adequate, then adopting it to observe new phenomena, gain new insights, develop new analytical methods and tools, and so further enlarging the scope of the phenomena that can be interpreted coherently. In the process, through communication and collective information processing each group organizes its way of life, aligning its members by collective adoption of a set of behavioural dimensions, conceptual categories that are externally expressed in languages, technologies, institutions and ways of interacting with nature. That alignment enables the group's members to function as a society.

This is where Iriki's concept of "extended epigenetic evolution" (2019) comes in. In the process of expanding the inside niche (the human information-processing capacity), some of that process is delegated to language, technology, the environment etc. Artefacts and concepts, for example, fix certain kinds of information processing in the material or conceptual realm by 'crystallizing' it in specific 'tools for thought and action' that the actors involved adopt. Both artefacts and intellectual concepts are such tools. Their structure determines that certain conceptual manipulations or actions in the outside realm are dealt with in pre-determined ways, and thereby circumvent part of the information-processing that is necessary to undertake those activities, alleviating the overall information processing load. In other words, part of the mind's information-processing is both routinized and displaced outside the mind. In societal dynamics, the same function is fulfilled by the establishment of conventions and institutions. These, too, 'routinize' parts of the information processing that is needed to function adequately in a particular society.

Categorization and the interaction between inside and outside niches

In the interaction between what Iriki calls the inside and outside niches, the dynamics of categorization play an important role. To explain these, I will use a simplified model of categorization that is based on the work of Tverski and others in Kahnemann's team at Stanford, studying decision-making under uncertainty (Tversky 1977; Tverski and Gati 1978; Kahnemann et al. 1982). On the basis of their conclusions, one can argue for the following model of categorization (Fig. 6). For a more extensive summary of the work, see van der Leeuw 2019a)

Categorization depends on combining a number of phenomena into a group that can be labelled by adopting one or more of its characteristics as a nomer. That process requires pattern recognition, that is a comparison between similarities and dissimilarities among the phenomena being observed. Once an initial comparison between unknown phenomena has led to the tentative establishment of one or more categories, these categories are tested against other phenomena to establish which phenomena might be subsumed in them and which would not. In the first phase of the process, the category is the subject and the phenomena are the referents. There is a bias in favour of similarity: what might unite the observed phenomena so that they can be grouped into a category. But when the relevant category is firmly esta-

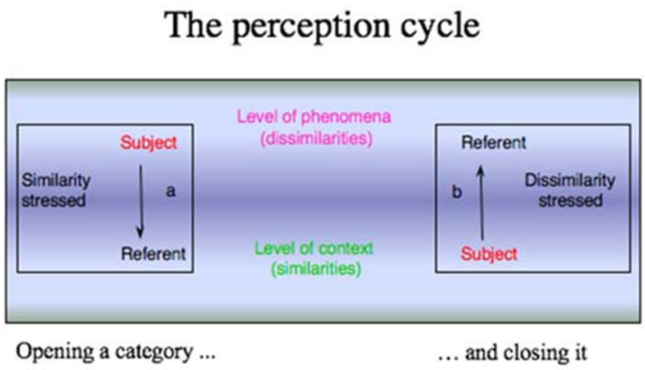

Figure 6: *Category formation according to Tverski and Gati 1978 (illustration from van der Leeuw 2019a)*

blished, the process is inverted: the categories become the referents and the phenomena the subjects, so that the comparisons are biased towards dissimilarity, and it is determined which phenomena, after all, did not belong in the categories established.

Such a shift from open to closed categories was observed linguistically in detail by anthropologists El Guindi and Selby (1976) in Oaxaca. The open categories were in the process of categorization and summarized situations where it was known what might fit in the category, but not yet what in the end would not. The closed categories expressed situations where both, what might fit and what in the end would not, were known.

We all know this phenomenon in our scientific work. When faced with unknown phenomena, we first create open categories by developing hypotheses about those phenomena. Little by little, we then whittle away at the phenomena concerned by the hypotheses, in order to get a better handle on them. In so doing, we emphasize what seem the most important dimensions of the phenomena concerned, thus slowly transforming the hypotheses into definitions (closed categories) in which we describe them.

Combining these ideas with the ones developed by Iriki (2019) about the construction of inside and outside niches sheds an interesting perspective on the articulation of the information-processing apparatus and the context in which it operates. The fundamental conception is that of two-way niche construction (Iriki 2019). But it understands niche construction in a way that is not normally part of the reflection it evokes in biology and ecology (Odling-Smee et al. 2003). Notably, it conceives of two dynamic niches, an internal one (comprising of the entire information-processing apparatus, including both mental and substantiated external elements) and an external one (the context of that apparatus), which interact and resonate with each other. In that sense, it is not unlike the self-nonself approach developed by Murase (2018).

As entry point for this subject we can take the ideas developed by Arthur (2015), who distinguishes 6 phases in the emergence of any new technology. What is interesting is that the role of the artefact in the relationship between the two niches shifts:

1. A novel technology appears. It is created from particular existing ones, and enters the active collection [of technologies] as a novel element.
2. The novel element becomes available to replace existing technologies and components in existing technologies.
3. The novel element sets up further "needs" or opportunity niches for supporting technologies and organizational arrangements.
4. If old displaced technologies fade from the collective, their ancillary needs are dropped. The opportunity niches they provide disappear with them, and the elements that in turn fill these may become inactive.
5. The novel element becomes available as a potential component in further technologies – further elements.
6. The economy – the pattern of goods and services produced and consumed – readjusts to these steps. Costs and prices (and therefore incentives for novel technologies) change accordingly.

Focusing on the conceptual dimensions involved rather than their material manifestations, one can easily see how at each of the steps involved the cognitive space of society has changed, expanding in some ways (the concepts and experiences behind the new technologies) and contracting in others (the concepts that were instantiated in pre-existing technologies and behaviours that are 'lost').

How does categorization impact on the interaction between the inside niche (the information-processing apparatus, both ideational and material) and the outside niche (its environment)? The basic dynamic is one where observations concerning the environment create or modify (aspects of) the information-processing apparatus, and the latter modifies the environment through the impact of human beings on that environment.

If the focus is on observing unknown phenomena in the outside world, initially the comparison will emphasize similarity. In the inside (information-processing) niche, this leads to the construction of a simplified, initially open, exploratory hypothesis about phenomena in the outside world. Subsequently, when that hypothesis is considered validated ('closed'), it changes status – instead of being considered tentative and hypothetical, and located at the edge of what is accepted as 'known', it shifts its location to the core of what is known, and becomes an accepted tool in further information-processing. In its interaction with the environment, the attention will now be focused on phenomena that can be distinguished as different from the tool just constructed. That may give rise to modifications, or even to the development of another information-processing tool, while many phenomena that do not fit the information-processing tool remain unobserved.

But as the processing apparatus inevitably is a simplification based on only part of the total dimensionality of that external niche, applying it will have a number of unintended consequences, many of which remain initially hidden from view and will manifest themselves only much later. Once that occurs, the cycle starts again. New open categories are created by searching for patterns among those unintended consequences, with a focus on similarities. There are some important insights to be gained in looking at things in this way.

First, it explains that the inside niche (the realm of ideas) always consists of a reduced set of dimensions compared with the outside niche (the environment), and that the selection of dimensions involved is always biased towards similarities. That explains the trend towards reductionism which is inherent in our perception of the environment.

Second, it also explains why the outcome of our interactions with the environment is always partly unexpected. As Lane and Maxfield argue (2005), it is subject to "ontological uncertainty". This is particularly evident when we think about the introduction of inventions in society. The outcome is always different from what was expected.

Third, the accumulation of the unintended consequences of our actions leads, over the long term, to an incapacity of us as individuals, or of our human societies, to deal with these consequences using the existing models in the realm of ideas (the inside niche) that have generated them. We experience such situations as 'crises' or 'tipping points'; times at which the models need to be radically changed. In science, we call such moments 'paradigm shifts.'

Fourth, the transformation of an exploratory hypothesis into an accepted information-processing tool in the core of the realm of ideas is a regular – but underexplored – part of the evolution of technologies. It can shed an interesting light on the cascades of innovations that often follow a first, completely paradigm-changing, invention.

A modern technological example

In this section, I will now try to illustrate in detail how this works by referring to a technological example that is presented by Arthur (2015). The basic assumption of that case study is that all artefacts are both *created by* information processing (as Roy Rappaport used to say (pers. comm. 1976): "creation is the simultaneous substantiation of form and information of substance), and *serve as information-processing tools* (because they reduce the information load required to fulfil actions by fixing in part how these are executed). In the process of serving as information-processing tools, the artefacts are transposed from part of the *external* niche to a hard-wired part of the *internal* information-processing niche. As argued above, their role in the interaction with the outside niche shifts from being 'open' to being 'closed' (van der Leeuw 2019a), from being an idea or domain to be formulated, created or explored to being a material tool in further exploration. That in turn triggers a change in the relationship between it and the outside world. As long as the category exists in the outside world, the emphasis in its relation with the inside niche is on similarities between it and the existing realm of ideas that trigger resonance, while when it becomes part of the inside niche, the emphasis in its relation with the outside world is focused on differences.

Let us now look at this process for one of the major technological revolutions of the past two centuries – the emergence of steam-driven long-term transportation, initially in the form of trains and later also steamships. In that process, one can distinguish the following steps.

1. The invention of the steam engine, combining a range of earlier inventions such as the use of coal, the invention of the piston and the wheel, the emergence of knowledge about the physics of pressure, etc. Existing information-processing tools are combined into a novel one.
2. The steam engine first becomes available to replace animal-based energy as a means of evacuating water from coal mines, and of propagating transportation on land. This in turn leads to the construction of the railroads, linking societies and economies over very long distances, such as in North America, Siberia and the Near East. The new means of transportation facilitates long-term movement, and therefore widens the perimeter over which human beings interact or exchange goods with each other. In that process, the now closed entity of 'a steam engine', transforms the outside niche (the environment), generating unintended consequences.
3. Among these are on the one hand further wishes (new dimensions in the internal niche of the realm of ideas), such as the wish to go faster and further, to be more comfortable, to enhance the volume of the trains or ships so that they can handle more goods or people. And on the other hand, on the engineering side (in the material world, the external niche), it elicits all kinds of technological challenges that are met in the following decades.

   One could also see the invention of the automobile as a result of this, as it facilitated mechanized overland movement of people and goods beyond the railways. And that led to Ford's invention of the conveyor belt and standardized mass production, but also major air pollution and, a century later, the challenge of climate change. The interaction between demand (challenges from the outside niche) and supply (inventions from the inside niche) is fundamental in these processes.

4. As the horse-drawn coach disappeared, initially its name and organizational structure (two face-to-face benches with doors on both sides of the train car) were embodied in trains, but ultimately it proved to be more efficient to replace this by long train cars with doors only on the ends. Thus, while change in the outside niche occurs, a dimension of the inside niche maintains at least for a while its old place in the information-processing realm. Ultimately, the word 'coach' is only retained for a particular level of comfort (equivalent to 3rd or 'economy' class). And as steam is replaced as a source of energy, by diesel fuel or electricity, a whole range of supplying tools such as water reservoirs to refill steam locomotives at all stations, or coal-carrying cars behind the locomotives, become obsolete. Ultimately, this is also the case for professions (such as stokers). Thus, part of the external niche is eliminated.
5. A little while later, steam engines are placed on board of ships crossing the Atlantic, reducing the time needed to cross this ocean. In idea (steam engines as sources of propulsion) is applied to another part of the external niche, resulting in new trade patterns, new products in places
6.

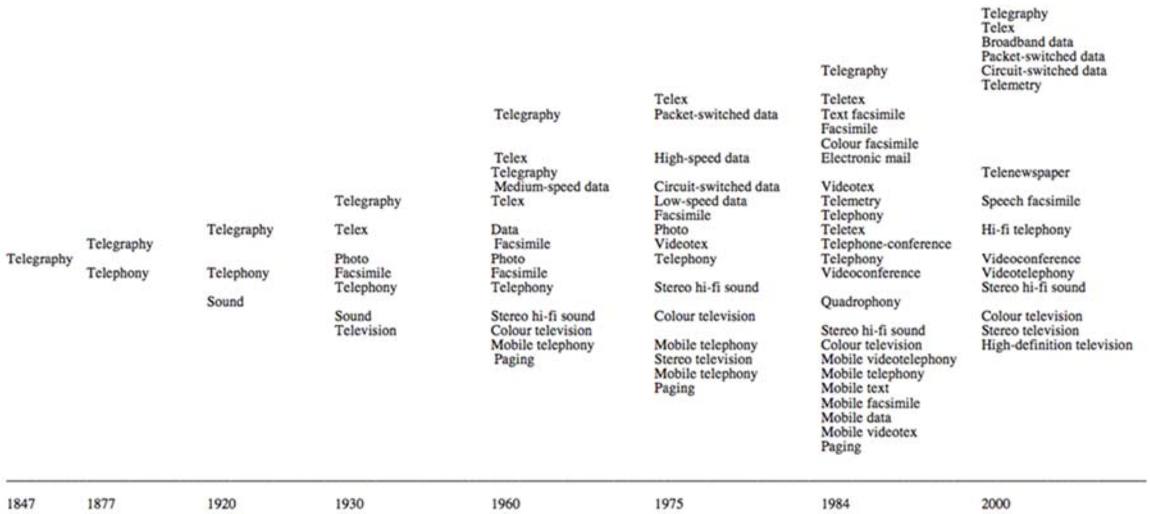

Figure 7: *An initial invention (the telegraph) gives rise to a whole cloud of other telecom inventions according to the process described in the text*

where they were until then not available, etc. Because of the danger of fire on board of ships, it also leads to the construction of iron ships. The need to remain in contact between distant locations in turn leads to the telegraph (with cables along the rail tracks), and later, to radio communications. All these are profound changes in the external niche that have been triggered by changes in the information processing apparatus – the internal niche.

7. All these inventions also change aspects of the structure of the economies involved by altering prices, production patterns, localization of industries, the nature of markets, etc. This can, in turn, trigger new novelties in behaviour, but also in the legal system (contracts), etc. According to the anthropologist Polanyi (1944), it ultimately even leads to an inversion of the relationship between society and the economy, from a situation where the economy serves as 'oil' in the society to make it function, to a situation where the society serves the economy.

In a different domain, figure 7 shows how, from an initial invention of electrical communication in the form of the telegraph, a whole tree of inventions has emerged by, at every step, repeating the above process of introduction in the 'external niche', discovery of new, related, dimensions for the invention (enlarging the 'internal niche'), discovery of new, related, challenges in both niches (new ideas in the internal one, new challenges in the external one) , and then the invention of new solutions (changes in the external niche) that, in turn will lead to new challenges in both niches.

The information in this figure stops around 2000, and therefore only includes the run-up and the first phase of the paradigm shift in information-processing that is currently happening, which includes digital information processing, but does not include the full impact of the ICT revolution, as instantiated by the world-wide web, machine learning, artificial intelligence, the internet of things, etc.

Information load and processing structure

The example of the steam engine (as well as any other that one could take) shows how, over time, both the internal and the external niches would acquire many more dimensions and would grow in size, implicating more and more phenomena. That is, in effect, how one could explain the growth in complexity of the networks (among people, but also among ideas, materials, artefacts, technologies, language, institutions etc.) that distinguish early, small hunter-gatherer groups from our current, highly complex societies.

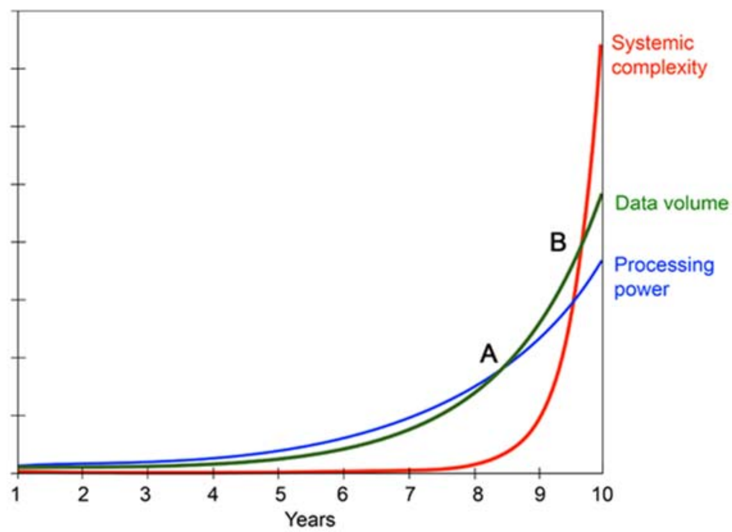

Figure 8: *The relationship between growth in processing power (what the internal niche can handle), volume of information processed, and overall system complexity taking the combinatorics of the system into account (after Helbing et al. 2017).*

In that growth process, of course, the total volume of information collectively processed in a group or society is also growing, and actually growing at a much faster speed than the number of interactions between network members because of the overall system complexity involved.

This is represented by a graph used by Helbing (2017) to illustrate the difficulties of gaining control over the total amount of information processed in the current day (figure 8). The relationship presented in the figure is in principle relevant for any time in the history of human information processing, but the temporal scale is intended for the present, and should be modified for the past.

This increase in the total amount of information maintained in any human system by continued processing very quickly exceeds the bandwidth of the processing structure. In part, that is due to the fact that once more people are involved in collective processing, communication between these individuals becomes a major constraint. Hence, there is continuous pressure on the communications structure of a society.

That pressure leads to phase transitions between collective processing structures, moving societies from egalitarian (everyone shares all information; there is a homogeneous "information pool") to hierarchical (some people process more information than others and have a bigger impact on decisions than others) to distributed (everyone has access to partial, incomplete information), to heterarchical (the various kinds of structures mentioned are combined in an overall setup). In another publication (van der Leeuw 2019, chapter 11). I have extensively outlined these changes and their consequences for the organization of the societies concerned, and it would take too much space to elaborate these transitions here. Ultimately, the pressure on the overall information processing capacity of our societies has led to the externalization of an ever-larger and more important part of the processing in the form of technology, institutions, routines, etc. In the natural environment, resources – once they are recognized as such and the processing tools have been developed to use them – also become part of the 'inside' niche of human information processing.

The relevance of technology here is that every artefact, every tool, every routine for using a particular tool, however simple or complex, is actually part of the total information processing apparatus as it reduces the uncertainty and the variability of the relevant operations concerned, and thus offloads some processing load from the STWM, transferring it to the tool and the routines needed to operate it.

The same can be said for institutions and socially accepted procedures – anything that is standardised as part of an institution or a routine procedure helps offload the information to be processed by the STWM. And we can extend this to the environment. The interaction between societies and their environments is one of ever expanding the reliance on environmental resources by designing the ways in which these can be exploited. The techniques and routines involved, including the clearance of 'wilderness' and the techniques used for agriculture, fishing, mining, metalwork etc., are in effect 'appropriating' the environment by including the relationship between it and society among the routines that simplify the society's information processing load. Hence my contention that we should see the societal evolution of the human species as a co-evolution between cognition, values, institutions, economy, technology and the relationship with the environment.

Societal information processing and its transitions

What follows is a highly abbreviated and simplified version of an argument that I have made *in extenso* in *Sustainability – Past and Future* (van der Leeuw 2019, Chapters 12 and 13) based on pioneering work by Huberman and his team (Huberman & Hogg, 1988; Huberman & Kerzberg 1985). In those chapters, I have looked at the dynamics of information processing as an instance of percolation dynamics in a network, and in doing so have been able to describe some of the major transitions in social dynamics as a function of the interaction between two independent variables, *connectivity* (μ, describing the shape or topology of a network) and the other *activation/relaxation* (α/γ, describing local interactivity in it). Varying these two parameters, one can model the transitions from (1) very small and ephemeral processing structures, via (2) more durable, but still very small ones, then to (3) larger networks that can vary considerable in size, and finally (4) to an all-encompassing network with very long-distance interactions.

Looking at the theoretical structures of these information processing networks is very interesting. I cannot, because of the limitations of space in a paper like this, treat these here *in extenso*, but I will try and give the reader some sense of the flavour of each different information-processing structure.

The first category involves all the nodes in the network (all the individuals in the group), which communicate (relate) with each other through many different channels (edges). In such a system, the information pool (the sum of all information flowing through the system) is homogeneous: everyone knows everything about everyone else in the group. Moreover, there are so many redundant channels of communication that any blockage in one or a few of these is essentially irrelevant This seems to have been the situation in many simple hunter-gatherer societies in which groups formed and dissolved regularly.

The second category still consists of very small groups, and involves all the nodes, but persists longer. One could think of small groups of people settled near regularly recurring or permanent resources so that the information-processing channels gain in persistence over those of mobile groups. The information pool among them is still very homogeneous, the redundancy is great, and the stability in the membership of the groups is greater than in the last case.

Essential for the correct understanding of the third category is that the groups involved are too large to maintain general control over information processing, or a homogeneous information pool. In all of them, information processing is hierarchically structured, which means that some members of the group (at the top of the hierarchy) have much more information at their disposal, and more control over the behaviour of the group, than many of the others (at the bottom of the hierarchy). The size of the groups, both in the model and in reality, varies hugely, and so does the efficiency of the information processing. But it is important to realize that the addition of a single hierarchical level to the group causes the information to spread on average exponentially faster. Huberman and Kerzberg (1985) call this effect 'ultradiffusion'. Other aspects of these processing structures, such as the impact of their symmetry, their specialization and the like are discussed in van der Leeuw (2019).

The next transition, to a very large network with long-distance interactions is based on the availability to everyone of partial information (which varies between individuals), so that no-one is in control of the system as a whole. It is what Simon (1969) calls a 'market-based' system. No one knows which members of the group may communicate with which others, or what information may be communicated. Because decision-making in this situation is always based on partial information, uncertainty and risk can fluctuate considerably. This mode of processing allows for larger groups to be integrated than the hierarchical one, and also for more flexibility. Beyond a certain number of participants, such networks may create clusters in which participants are more closely interactive than they are with individuals in other clusters.

Highly relevant to us in the modern world is the next information-processing structure, which is found in the largest, most complex societies: the heterarchical one. It occurs beyond a certain number of people in the system, and combines hierarchical and market-based (partial information control) elements. Such a combination in effect optimizes certain aspects of both modes of information processing, and thus circumvents some of both systems' drawbacks. In this kind of information-processing structure, there is no control at all over the whole group, but subgroups cohere by sharing values, approaches, techniques and specific kinds of environments.

The emergence of different information filters

In this paper, my main purpose has been to apply the "self-nonself " (endo-exo-) approach proposed by Murase (2018) as a general model for the evolution of living beings to my ideas about the evolution of human information processing as expressed in van der Leeuw 2019. In this first attempt, clearly there are many issues that have not been discussed, and in particular, the transitions in information processing among different classes of plants and animals have been omitted, simply because I am not a biologist.

But we can begin thinking about those transitions by considering human information-processing. A core element of the interaction among individuals, groups and societies on the one hand, and their environments (material, social, ideational) on the other, is that fact that the behaviour of human systems is in part determined by genetic, cultural, social and experiential filters.

Among the ***genetically determined*** filters are for example the fact that human beings only are able to perceive certain aspects of the full light spectrum, or the fact that they are bipedal, have two hands and have their eyes in the front of their face. But those are merely examples of a much wider range of genetic filters that limit and bias humans' perceptions and decisions, such as the range of frequencies of the electromagnetic spectrum they can experience (and thus the colours they can see), or the sounds that they can hear, and over which distances they do so. Of course all plants and animals also have such genetically determined filters. Generally speaking these filters operate without leaving the individuals much choice – the information thus filtered triggers predetermined (instinctual) responses with a very narrow bandwidth.

Among the ***culturally (societally?) determined*** filters are at the most basic level aspects of people's 'world image'. For example those aspects embedded in their belief and value systems, in the dominant narratives and institutions that structure their society, in the vocabulary and syntax of their language and in their technology. But other ones are the distinction between the two major systems in the world for crushing grains into flour, as well as different religions or different conceptualizations of time and space, etc. Such filters are the result of the path-dependent histories of the different cultures, and allow for considerable variation and choice. But that variation is constrained by the things the members of a culture have never been confronted with, and thus have not had occasion to think about. The bandwidth is much larger, but even if it is not experienced recurrently, it is nevertheless limited. Choices can be made, but not every option is permissible.

Groups within societies also have their own filters, such as the scientific methods our societies have developed to interpret and communicate about a wide range of phenomena, including technical terms, jargons, dialects, and specific customs such as scientific evaluations. Like cultural filters, these are sustained by social relations that maintain certain communities within different cultures together. Many such communities are related to the roles the members of their group fulfil in the society, such as their professions, but they can also be value-based, as in the case of religions. As any number of such groups together constitute a society that partakes in a particular culture, the bandwidth of the group's information processing is a subset of that of a whole society's culture and has a narrower bandwidth that the culture as a whole.

Individual filters are the result of differences in the growth of individuals' background, including their individual interpretations of the world around them, their family background, their schooling, and their experiences in life. The bandwidth of such individual filters varies greatly, but is always narrower than that of a collective that processes information together.

The first set of filters is, within a relatively short time-frame of centuries, unchanging and sets fundamental constraints for the other filters. Some of these are well-known, such as the ones involving the nature, shape and functional capabilities of our bodies, but others need further investigation, notably those that are genetic, but do not have such explicit manifestations.

The latter three categories of filters can vary as the result of social interactions in networks of different sizes (parts of multi-nets), anchored in the 'grille de lecture' determined by the genetic filters. These (and possibly other) filters are superimposed and determine to a large extent how individuals and groups will decide on their interactions among themselves or with the external world. Together, they shape a large proportion of the values, affordances and constraints of signal recognition, signal processing and signal communication among individuals and groups within societies.

The fact that among humans there are a number of such filters (and there are probably other ones than were mentioned here) makes me wonder whether one could identify different information-processing filters among animals, for example. I would argue that all animals have genetically determined filters, but one could argue that primates, for example, also have cultural or group ones. Are there other filters that are particular for other living species?

Last words

As mentioned at the outset, this paper is a first attempt to develop a perspective that could apply to all life-forms, based on the idea of signal-processing. It is very much a work in progress, a set of loosely connected ideas that in my opinion have sufficient in common to encourage the exploration of an approach like this. There are many holes, and it would be easy to shoot all this down, but because the interactions I had with Prof. Murase, the editor of this Journal, it seemed appropriate to bring these ideas together, even in a very primitive and incomplete form, in the *Journal of Integrated Creative Studies.*

References

Aanen, D.K. & P. Eggleton, 2017. “Symbiogenesis: beyond the embiosis theory” *Journal of Theoretical Biology* 434:99-103, doi: 10.1016/j.jtbi.2017.08.001.

Atmanspacher, H., & G.J. Dalenoort (eds.), 1994. *Inside Versus Outside: Endo- and Exo-Concepts of Observation and Knowledge in Physics, Philosophy and Cognitive Science*, New York: Springer

Arthur, W. B., 2015, *Complexity and the Economy*, Oxford: Oxford University Press

Bateson, G., 2002, *Mind and Nature: a necessary unity*, New York, NY: Hampton Press

Bretscher, M. S., 1987. “How animal cells move”, *Scientific American*, 257 (6): 70-76

Churchman, C. W. 1967. “Guest editorial: Wicked problems.” *Management Sciences* 14 (4): 141–142.

Dautry-Varsat, A. & H. F. Lodish, 1984. “How receptors brings proteins and particles into cells”, *Scientific American*, 250, No. 5, 52-58

Doidge, N. (2015) *The Brain’s Way of Healing: Stories of Remarkable Recoveries and Discoveries*, Harmondsworth (UK): Penguin Books

El Guindi, F. & H. A. Selby, 1976. “Dialectics in Zapotec Thinking” in *Meaning in Anthropology* (K. Basso & H. Selby eds.), Albuquerque NM: School of American Research

Helbing, D., B. S. Frey, G. Gigerenzer, E. Hafen, M. Hagner, Y. Hofstetter, J. van den Hoven, R. V. Zicari, & A. Zwitter. 2017. “Will democracy survive big data and artificial intelligence?” *Scientific American*, February 23. Available at: www.scientificamerican.com/article/will-democracy-survive-big-data-and-artificial-intelligence/?redirect=1.2017

Huberman, B.A. & T. Hogg, 1988. “The behaviour of computational ecologies.” In: *The Ecology of Computation* (Huberman, B.A. ed.), pp. 77–115. Amsterdam: North-Holland Publishing.

Huberman, B. A. & M. Kerzberg. 1985. “Ultradiffusion: The relaxation of hierarchical structures.” *Journal of Physics* A 18: L331–L335.

Iriki, A., 2019. “The Brain in the Ecosystem: Cognition, Culture, and the Environment” video of *Kavli Plenary Address at International Convention of Psychological Science*, March 2019. https://www.youtube.com/watch?v=XdX0xkPxS0c

Izutsu, T., 1975. “The Interior and Exterior in Zen Buddhism”, in: Correspondences of Man and World, eds. A. Portmann, R. Ritsema, *Eranos Yearbook 1973*, Leiden: E.J. Brill.

Kahnemann, D., P. Slovic, & A. Tverski, (eds.). 1982. *Judgment Under Uncertainty: Heuristics and Biases.* Cambridge: Cambridge University Press.

Lane, D. & R. Maxfield. 2005. “Ontological uncertainty and innovation.” *Journal of Evolutionary Economics* 15: 3–50.

Margulis, L., 1970, *Origin of eukaryotic cells;: Evidence and research implications for a theory of the origin and evolution of microbial, plant, and animal cells on the Precambrian earth*, New Haven: Yale University Press

Margulis, L., 1981, *Symbiosis in cell evolution*, San Francisco: W.H. Freeman

Margulis, L. & D. Bermudes, 1985 “Symbiosis as a mechanism of evolution: Status of cell symbiosis theory”. *Symbiosis* 1:101–124.

Mitchell, M. 2011. *Complexity: A Guided Tour*. Oxford: Oxford University Press.

Murase, M. 2018 “A Self-Similar Dynamic Systems Perspective of “Living” Nature: The Self–Nonself Circulation Principle Beyond Complexity”, Springer, Singapore

Odling-Smee, F. J., K. N. Laland, & M. W. Feldman. 2003. *Niche Construction: The Neglected Process in Evolution*. Princeton, NJ: Princeton University Press.

Polanyi, K. 1944. *The Great Transformation*. New York: Farrar & Rinehart. [2nd ed., T*he Great Transformation: The Political and Economic Origins of Our Time*, Foreword by Joseph E. Stiglitz, 2001, Boston: Beacon Press].

Prigogine, I. & G. Nicolis. 1980. *From Being to Becoming: Time and Complexity in the Physical Sciences*. San Francisco: W.H. Freeman.

Rappaport, R. 1977. "Adaptation and maladaptation in social systems." In: *The Ethical Basis of Economic Freedom* (I. Hill, ed.) pp. 39–79. Chapel Hill, NC: American Viewpoint.

Read, D.W. & S.E. van der Leeuw, 2009. "Biology is only part of the story ...." In: *Sapient Mind* (A. C. Renfrew & L. Malafouris, eds.), pp. 33–49. Oxford: Oxford University Press.

Read, D.W. & S.E. van der Leeuw, 2015. "The extension of social relations in time and space during the Paleolithic and beyond." In: *Landscapes in Mind: Settlement, Society and Cognition in Human Evolution* (F. Coward, R. Hosfield, & F. Wenban-Smith, eds.), pp. 31–53. Cambridge: Cambridge University Press.

Rothman, J. E., 1985. "The compartmental organization of the Golgi apparatus", *Scientific American*, 253 (3) 84-89

Shannon, C. E. 1948. "A mathematical theory of communication." The Bell System Technical Journal 27: 379–423.

Simon, H.A., 1969 [2nd ed., 1983; 3rd ed., 1996]. *The Sciences of the Artificial*. Cambridge, MA: MIT Press.

Tverski, A. 1977. "Features of similarity." *Psychological Review* 84: 327–352.

Tverski, A., & I. Gati. 1978. "Structures of similarity." In: *Cognition and Categorization* (E. Rosch & B. B. Lloyd, eds.), pp. 79–98. Hillsdale, NJ: Lawrence Erlbaum.

Varela, F. J., E. Thompson & E. Rosch, 1991. *The Embodied Mind: Cognitive Science and Human Experience*, Cambridge MA: MIT Press

van der Leeuw, S.E., 2000. "Making tools from stone and clay." In: *Australian Archaeologist. Collected Papers in Honour of J. Allen* (T. Murray & A. Anderson, eds.), pp. 69–88. Canberra: ANU Press.

van der Leeuw, S.E., 2007. "Information processing and its role in the rise of the European world system." In: *Sustainability or Collapse*? (R. Costanza, L. J. Graumlich, W. Steffen, eds.), pp. 213–241. Cambridge, MA: MIT Press (Dahlem Workshop Reports).

van der Leeuw, S.E., 2019a "The role of narratives in human-environmental relations: an essay on elaborating win-win solutions to climate change and sustainability", *Climatic Change* (Special Issue on win-win solutions to climate change, D. Mangalagiu, A. Bisaro, J. Hinkel, and J. D. Tàbara, eds.). CLIM-D-18-00612R1, DOI: https://doi.org/10.1007/s10584-019-02403-y

van der Leeuw, S.E., 2019b *Social Sustainability, Past and Future: Undoing Unintended Consequences for the Earth's Survival*, Cambridge University Press, ISBN 978-1-108-49869-2 (Hardback) DOI: 10.1017/9781108595247; open access: https://www.cambridge.org/core/books/social-sustainability-past-and-future/811395DC3A8D82EAD39C45657B2FD1AD