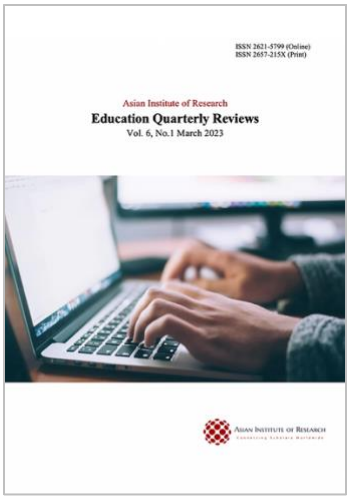

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# Learning: An Evolutionary Perspective

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**Abstract**
From an evolutionary perspective, this article presents a synthesis of the work on learning and advocates conceptual changes. It distinguishes several levels of learning: genomic, sensorimotor and symbolic. It also suggests a re-examination of the concepts of artifact, algorithm and information, extending them to all living things and differentiating them according to the levels of learning. These modifications are justified by the numerous discoveries that have modified our representations during the last decades. Epigenetics has shaken the relationship between the innate and the acquired, neuroscience has made it possible to go beyond behaviorist dogmas, ethology has brought humans and animals closer together, social learning has emerged as a basic skill leading to languages and cultures, and psychology has shed more light on the roots of the symbolic in the sensorimotor. Each of these different advances in our knowledge has an impact on the conception of learning and invite us to adapt our conceptual tools. Such an adaptation should allow us to better apprehend the digital revolution and its learning modalities.

**Keywords:** Learning, Evolution, Social Learning, Education, Artifact, Algorithm, Information

## 1. Introduction

In recent decades, several scientific contributions have called to reconsider learning: epigenetics have shaken our representations of the innate and the acquired; cognitive neuroscience has sidelined classical behaviorism; ethology has revealed the existence in animals of social learning and of cultures; child psychology has better identified the articulation between the sensorimotor and the symbolic; finally, humans have developed digital machines capable of new forms of learning, thus changing their relationship to the world.

Reflecting upon learning today means questioning conceptions that impede the integration of these new developments. This article focuses on the classical oppositions between the innate and the acquired and between the living and the technical, the latter mobilizing the notions of *artifact, tool, information* and *algorithm*. This approach implies considering the biological and neural realities related to learning that are now part of human culture. Such an interdisciplinary detour has become necessary. The conceptual redefinitions proposed here are made within the framework of an evolutionary vision. This vision distinguishes between genomic, sensorimotor and symbolic learning, each of which is both connected and separated by emerging steps (Petitat, 2020). This update is the first step towards an interpretation of the relationship between digital revolution and learning on an evolutionary scale.

## 2. Genomic learning

The classical synthetic theory of evolution relates the evolutionary dynamics of species to random mutations and selective pressures. Over the past decades, this credo has repeatedly had to adapt, for several reasons:

- Starting in the 1990s, biologists uncovered epigenetic mechanisms. These mechanisms, which modify gene expression in a reversible and partially transmissible way, are related to the organisms' own experiences. They can be assimilated to genomic learning, thus introducing intra- and inter-generational plasticity (Baugh & Troy, 2020, Burton et al., 2021). Here, innate and acquired are in close dialogue.
- For some time, the learning abilities of many unicellular organisms have intrigued researchers. Other mechanisms, different from epigenetics and still poorly understood, are at work here (Boussard et al., 2019; Dexter et al., 2020; Fleig et al., 2022; Gershman et al., 2021).
- The *gene-behavior* and *gene-culture coevolution hypothesis*, which suggests that behaviors learned without modifying genes can exert selective pressure on genetic mutations and become evolutionary drivers, introduces an interesting interactive evolutionary pattern between innate and acquired (Richerson & Boyd, 2005; Gupta et al., 2021; Aguilar et al., 2019; Nolfi & Floreano, 1999).
- Research has also shown the existence of inter-species transfers of genetic know-how. Each lineage is therefore not obliged to invent or reinvent everything all over again. These transfers, made possible thanks to the universality of the genetic code, have sometimes caused decisive evolutionary leaps (notably during endosymbiosis). Learning from others is the basic pattern of what we call *social learning*. By producing GMOs, humans deliberately organize such transfers.
- Finally, the *neutralist theory of evolution* (Kimura, 1968) has shown that most mutations have little or no effect on survival and reproduction. This observation reduces the relative importance of the mutations-selections process and increases that due to genetic drift made of unpredictable ecological hazards such as geographical fragmentations of populations, epidemic ravages, cataclysms, etc.

The radical opposition between hereditary genetic determinisms and learning does not account for this new landscape. In order to overcome this shortcoming and in the interest of conceptual homogenization, it is preferable to include the dynamics of genetic evolution in the concept of *genomic learning*. Behavior can be learned, both at the level of genes, which can be transmitted from one generation to the next and at the level of intra-generational experiential learning that mobilizes their expressions. It is the modalities of learning that change. A clear division between innate and acquired impedes the development of an encompassing vision articulating different learning dynamics (Hosken et al., 2019; Weitekamp & Keller, 2019).

### *2.1 Artifactuality at the cellular level*

Why not consider proteins as a variety of artifacts produced at the cellular level? Traditionally, the notion of artifact refers to *objects made by humans intentionally, in order to meet certain goals*. It implicitly refers to the opposition, attributed to Aristotle (The *Nicomachean Ethics*, 1997, 1140a), between nature (beings that exist by themselves) and culture (objects related to human arts). This definition has often been criticized. It no longer satisfies ethologists, who have underlined a gradation in animal intentionality and culture. The notion of object is not clear either: do vocalizations or meaningful gestures fall into the category of artifacts? Should the products of mental operations be included? More generally, should all behaviors be included? The dimension of functionality is also problematic, since waste, fabricated and rejected by biological organisms is, for them, devoid of function. Finally, biological engineering raises still other questions. The *Escherichia coli* bacterium, a natural organism, becomes an artifact when modified to produce insulin. The latter can be considered an artifact of the artifact. Not only do GMOs produce artifacts, but their genomes can be partially considered as artifacts.

We must come to terms with the fact that the old concept of artifact, which refers to a "paleolithic categorization" (Sperber, 2007), belongs to the past. It refers to an anthropomorphic ontology, at odds with our present knowledge and practices. Either this concept is abandoned, or it calls for a consequent redefinition that makes it compatible with current epistemic requirements. The present paper opts for this last solution.

Jacques Monod, in *Chance and Necessity* (1972, 9), already suggested a radical broadening of the notion: "Every artifact is a product made by a living being which through it expresses, in a particularly conspicuous manner, one of the fundamental characteristics to all living beings without exception: that of being *objects endowed with a purpose or project*, which at the same time they exhibit in their structure and carry out through their performances (such as, for example, the making of artifacts)".

With this perspective in mind, even unicellulars produce artifacts. Thus generalized, the concept of artifact encompasses all creations of living beings, material, immaterial or behavioral, internal or external, from the proteins made by bacteria to today's computers. This extension, of the same generality as that of living beings as a whole, will undoubtedly seem exaggerated to some. It is proposed here to help overcome the erroneous anthropocentric vision by which humans are the almost exclusive bearers of technical capacity and inventiveness. This extension of the concept of artifact, which implies an analogous extension of that of "technique", calls for its specification depending on whether it refers to a molecule, a behavior, a tool, a word or a narrative.

Such a vision implies already constituted biological subjects. It must be completed by including two fundamental processes: reproduction and self-production. Living beings are themselves their own artifacts. They self-transform by modifying the production of their own artifacts. The circular relationship between “technique” and “subject” is already present at the unicellular level.

Tools are a sub-category of artifacts. They are products that repeatedly serve to accomplish one or more functions. They can be internal, such as the enzymes of unicellulars, or external, such as spider webs or bird songs. This definition differs considerably from Beck's (1980) anthropomorphic definition, which defines the tool as external to its user, detached from its support, held and correctly oriented in order to modify the form, position or state of another object, organism or the individual himself. Such a definition automatically excludes unicellulars and most non-human multicellulars. It has proven cumbersome, as it is associated with very dissimilar levels of cognition – from birds adjusting twigs to extract insects to ants dipping grains of sand in an edible liquid to transport it to their anthill – while excluding the sometimes very sophisticated construction of birds' nests, field mice galleries, etc. Such a definition has frequently been questioned and proposals have been made to extend it as observations in ethology have accumulated (Cuevas Badallo, 2019; Preston, 1998; Gould, 2007; Borgo et al., 2013).

Alongside the tool, other categories of artifacts should be mentioned: *functional assignment artifacts* (the living being borrows elements from the environment without modifying them and endows them with specific functions), *compositional substance artifacts* (the living being fabricates simple elements that will serve as bricks in more complex constructions), and *waste artifacts* (the living being discards elements that it no longer needs). All of these artifacts are closely dependent on the genetic code, a core artifact which deserves special attention.

### *2.2 The genetic code, an immaterial but embodied artifact*

Nothing is more material than DNA, a polymer with its nucleic acids. Nor is anything more material than the fabrication of proteins by adding amino acids and folding. But how to classify the genetic code itself? It consists of corresponding relations between three by three combinations (triplets or codons) of four simple molecules (nucleotides), combinations that univocally refer to one or the other of the twenty amino acids that enter by linear addition into the composition of proteins. DNA itself is not a code but a macromolecule. A common but inaccurate shortcut is "DNA code". Indeed, a molecule becomes a code only if it is associated with a decoding process. Once Watson and Crick (1953) had described the DNA molecule, it took many years to discover how this helical chain was solicited and read by other instances in the cell.

The correspondence relations of the genetic code are not material, although they unfold their effects in a material way and can exist only with a material support. The immateriality of the codes is materially expressed in the bodies. The self-artifactual evolution takes place in the background of the immateriality of the codes and the materiality of the life and death of the bodies (or of their subdivision). It is possible to translate a genome into a binary language and record it on a computer, i.e., to move from a chemical medium *in vivo* to an electronic one *in silico*, and vice-versa (Gibson et al., 2010; Venter, 2013). However, the switch from one medium to the other is not innocent, since the *in silico* is cut off from the dynamics that characterize the *in vivo*. Each medium has its possibilities and constraints. To ignore this leads to dead-ends, possibly to the endangering of vital processes.

Information conceived outside of its media is an abstraction made possible by the symbolic revolution. In *Information, The Hidden Side of Life* (Dessalles et al., 2018), the authors rightly emphasize the immaterial aspect of information coding in the living kingdom. However, they tend to neglect the supports, by equating *in silico* with *in vivo* genomes. Moreover, when referring to physicalist conceptions of information, the authors reduce biological information solely to its physical transmission dimension, thus maintaining a confusion of levels and a reduction that has proven to be of little use to biologists (see below).

The genetic code came into being during the protohistory of life. Unfortunately, so far, the important quantity of research concerning the origin of life has not been able to provide any certainty enlightening this genesis. Between the physical and the biological, there is a grey zone where what belongs respectively to the living and the non-living seems undistinguishable (Lechermeier, 2019; Heams, 2019; Lafontaine, 2021). Between the first material systems capable of evolving and the first prokaryotic cells analogous to those we know today, it is likely that hundreds of millions of years passed. It is in this obscure zone that the immaterial relations of correspondence came to be, relations that characterize not only the genetic code but all the other subsequent codes of life.

The genetic code opens the door to both memorization and random-selective variations of algorithmic procedures. It is the primary invention on which all others depend. The genetic code acts as an operator of complexity between the physical and the biological. It constitutes the central device of genomic learning as a slow and continuous self-invention of biological subjects.

### *2.3 Physical information and biological information: the notion of algorithm*

In its most general sense, the notion of algorithm designates predefined ways of proceeding to obtain a particular result, thus including the procedure for making a protein as well as the recipe for a cake or the way to extract a square root. This notion is important to distinguish two types of morphogenesis. In the physical world, transformation processes are not guided by algorithms derived from learning: they result from the encounter of material objects under certain energy conditions. Even if the transformations take place in a specific order, no learning is involved. Physical information is linked to the laws governing the structure and transformation of matter and energy. Biological information holds a meta-position with respect to physics: it guides physical transformations by using coded procedures and biotechnical mediations that are invented, memorized and can be modified. A gene can be assimilated to an algorithm that guides the synthesis of a protein by mobilizing an internal chemical factory (composed of ribosomes and transfer RNAs). DNA gathers a large number of algorithmic instructions intended to frame the molecular fabrications that the metabolism needs. The coding relationships that underlie these algorithms can therefore be conventionally used to draw the boundary between the physical and the biological, two domains that differ in their dynamics of form-making or morphogenesis (the idea of inert matter is obsolete).

The conceptions of Claude Shannon (1948) and Léon Brillouin (1956) – who made the link with Boltzman's physical entropy – are often used as a reference when it comes to suggesting a scientific definition of information. However, they focus on the reduction of signal uncertainty (information loss and compaction) and neglect qualitative changes in information. This approach provides a transdisciplinary benefit that has largely fueled the hopes of cybernetics, by linking information and negentropy (Lafontaine, 2004). However, this advantage ignores the mutations of information during evolution. At the basis of these metamorphoses, the emergence of the living has promoted information to the status of coded procedural knowledge and know-how guiding physical transformations (Chapouthier, 2001, Bates 2005, 2006).

Nontheless, the procedural recipe alone is not enough: to transform something, the ingredients as well as the technical means are both necessary. When an algorithmic information guides a physical transformation, it induces a modification of the physical information thanks to a technical mediation (energy, an enzyme facilitating an intracellular chemical reaction, an appropriate gesture, a tool, a machine, etc.). This technical mediation must be invented and transmitted, which implies constraints of energy, manufacturing steps, etc., that must obviously respect the laws of physics.

### *2.4 In summary...*

Genomic learning occurs through several mechanisms, including mutations-selections, genetic drifts, modulation of gene expressions, gene transfers, gene-behavior and gene-culture interactions. Stochastic links are established between learnings at the individual level and their impact at the species level. Ideally, the study of learning should not omit to link these two poles. This is particularly important since it concerns the self-construction of living organisms.

At the heart of the system we find the genetic code. Genes can be considered as algorithms that may be activated to guide the synthesis of artefacts, in the form of complex molecules necessary for cellular life. During the transition between the non-living and the living, information acquires new qualities that make it capable of animating the morphogenesis of the living, which is different from that of the non-living.

"Technical" knowledge and know-how are constitutive of living beings, and have been present from the very beginning. Obviously, this does not mean that technical creativity in general can be reduced to that of unicellulars. The genomic, sensorimotor, symbolic and digital technical dynamics are separated by emergent disruptions. The naturalization of the technical, in the sense of reducing higher levels to the genomic, is therefore only of relative interest. To recall that the human species did not invent artifacts does not mean falling into a form of reductionist naturalism. Rather, it is a perspective that places mankind in the general evolution of life, with its continuities and ruptures (for a review of the discussions around the concept of emergence, see O'Connor & Wong, 2015). The fact of ignoring that life itself requires a meta-position, resulting in the elaboration of algorithms guiding physico-chemical transformation processes, deprives us of understanding the distant roots of the various technical revolutions that took place, as well as the current digital revolution.

## 3. Sensorimotor learning

Learning abilities have long been attributed to non-human organisms. There is no need to go back to the behaviorist theories, Watson's stimulus-response, Pavlov's conditioning, Skinner's trial-and-error and reinforcement. This current has gradually declined as cognitivist approaches and neuroscience have progressed, opening the neural black box and proposing more complete explanations. The following remarks are in line with this last perspective.

It is not the DNA memory that changes in the bird that has located a food source, but a second memory, neural, informed by its sensory capacities. The more the triptych formed by the bird's senses, its nervous system and its motor means help it to detect, locate and find a food site, and then to abandon it when it is exhausted, the better the bird will be equipped to survive. This dynamic of neuronal or sensorimotor learning is grafted on a genomic base. However, its tempo, directly connected to life experiences, differs from that of biological knowledge, which is slower, as it depends in particular on mutations, selections and genetic drifts. The nervous system quickly processes sensory data and draws behavioral conclusions. The gain is an experiential adjustment of behaviors, more rapid and subtle than genetic mutations and epigenetic modulations. The key condition is the plasticity of the recordings. The nervous system must be partly pre-shaped to know how to receive, process and send information, and partly indeterminate, to accommodate the diversity and instability of life settings.

Behavior, informed by life experiences, becomes a driving force of evolution, assisting in retaining neutral or advantageous mutations related to perceptual (tactile, visual, auditory...), neural (processing modalities) and motor (jaws, legs, wings, fins...) capacities (Piaget, 1978; Richerson & Boyd, 2005). Each pluricellular species defines itself according to this triptych and constructs in its own way the categories of space and time, form and light, color and sound, force and gravity, taste, smell, etc. Each species and each individual of each species builds a different sensorimotor world.

### *3.1 Neural codes and plastic engrams: the primary artifacts of the sensorimotor*

The neural memory, a sensorimotor equivalent of DNA memory, is highly plastic; it consists of *coded inscriptions* or *engrams*, which can be modified, confirmed or erased. The mechanism that allows such sensitivity to perceptions and activities is based on the modulations of the interactions between neurons, cells that are specialized in communication (on the origin of neurons, Musser et al., 2021). Since Ramón y Cajal (1894), reinforced by Hebb (1949) and confirmed by Kandel (2001), research has established and clarified that learning involves changes in neuronal connections. This is particularly true during the development of young subjects. For example, animals reared in an understimulated environment have fewer synapses and a reduced cortex compared to others reared in a richer environment (Rose et al., 2005). Processes, from perception to motor commands through neural processing, have so far yielded only part of their secrets. A brief review is necessary to recall a few basic points and to ward off simplistic schemes derived from computer science.

Sensory neurons record messages from sensory sensors and transmit them to the central nervous system by means of electrical signals. These electrical impulses, called *action potentials* or *spikes*, consist of brief changes in membrane potential, sometimes up to a hundred per second. Neurons are connected by thousands of *synapses*, consisting of a *presynaptic element* (with vesicles containing neurotransmitters), and a *postsynaptic element* (with receptors located on the neighboring neuron), which are separated by a tiny gap, the *synaptic cleft*. The action potentials provoke the injection of neurotransmitters into the synaptic cleft. These molecules are, in whole or in part, captured by post-synaptic receptors. These receptors in turn translate the chemical signals into positive or negative electrical charges. The receiving neurons each perform the sum of these multiple inputs; new action potentials will only be emitted if this sum exceeds a certain threshold. What happens in the synaptic clefts is therefore eminently important to understand neural dynamics. This communicative process, typical of chemo-electric neurons, is both stochastic (inter-neuronal molecules) and discrete (electrical discharges). Some purely electrical neurons are characterized by ultrarapid and direct connections (*gap-junctions*); they are very useful when, for example, motor cells are mobilized in unison.

Another important aspect is related to the cerebral processes of decomposition-recomposition. Sensory receptors split perceptions into multiple aspects (sound into frequencies, rhythms, timbres; space into edges, speed, orientation; facial features into distances between different points, etc.). These aspects are then processed by specialized neurons and neural circuits, to finally become the object of a synthetic recomposition. This mechanism allows to face the infinite diversity of multi-sensory perceptive configurations: rather than recording singular tables, which would very quickly clog the brain, this process records dimensions which, by combination, make it possible to reconstitute innumerable configurations. This analytical approach requires a wide variety of neurons, some dedicated to analyze and others to synthesize. Researchers have distinguished over a thousand types of neurons in the mouse neocortex (Shepherd et al., 2019) and over 130 types of neurons in the chick retina alone (Yamagata et al., 2021). This neuronal diversity also involves synapses; concerning this point, the inventory is still far from complete (Cizeron et al., 2020; Scholl & Fitzpatrick, 2020).

Identifying how neurons connect to each other through their synapses (connectome) is a necessary step to understanding brain activity. However, drawing such a map quickly proves insufficient for a number of reasons of which the most important are:

- the same sensory stimuli result in surprisingly different patterns of action potentials, attributable to previous learning and to "noise" of various origins;
- the numerous types of neurons and synapses multiply the complexity of neural circuits;
- besides the best known and most studied *neurotransmitters* (glutamate, serotonin, acetylcholine, dopamine, oxytocin...), hundreds of other molecules circulate in the nervous system and are often co-transmitted (Svensson et al., 2019);

- in synaptic clefts, fluxes are not uniform but are modulated by hundreds of interacting proteins, or *interactomes*. Unraveling these interactions and their links to ongoing activities presents daunting challenges (Rudenko, 2019; Hart, 2019; Südhof, 2018);
- a single neuron may participate in multiple neural networks corresponding to different activities. Not only does the geography of its synaptic connections change, but also, it seems, the properties of these connections (Spitzer, 2017; Stefanini et al., 2020);
- the neural landscape shifts continually and is therefore difficult to pin down. Most neurons change 5-10% of their synapses monthly; for some neurons, the percentage can be as high as 40% (De Paola et al., 2006). *Synaptomes*, which include all synapses, their types and locations, are permanently transformed (Cizeron et al., 2020);
- information does not always flow in the same usual direction, from presynaptic to postsynaptic: there are also *antidromic action potentials*, which move in the opposite direction and play a role in neuronal excitability (Trigo, 2019) ;
- brain processing of information involves not only neurons, but also, to a lesser extent, other brain cells, the glial cells. For many years, researchers have confined the latter to assistance functions, energy supply, waste evacuation, immune surveillance, etc. However, several recent studies emphasize their participation in information processing (Henneberger et al., 2020; Fields & Bukalo, 2020; Li et al., 2020; Taylor et al. 2021);
- finally, learning changes the landscape of neuronal connections and thus the processing of new information.

Assuming that there is an identical way of coding sensory inputs, this code will be applied differently depending on the situation, previous learnings, filters mobilized according to the goal pursued, etc. The computations that accompany *in situ* the unfolding of a behavior will therefore not be the same either.

Under these conditions, cracking the neural codes related to various types of activity (displacement, identification of a generic or singular shape, etc.) is a true challenge. An important step in this direction was made when the types of neurons involved in mental mapping were identified (Moser & Moser, 2016). Another breakthrough took place when the registration of facial dimensions were understood (Chang & Tsao, 2017). However, the details of the exchanges within the neural circuits involved, as well as the synthesis of the results between the different circuits mobilized, remain to be clarified; this requires the development of particular statistical tools, inspired in particular by graph theory.

In short, the dynamics of learning are based on neuronal plasticity, which is much more refined and sensitive than genomic plasticity. At the heart of the sensorimotor triptych, engrams are created and modified at the crossroads of genomic inheritance and life experiences. Each brain is unique (Van de Ville et al., 2021). Behavioral plasticity is rooted in variations in neuronal exchanges. These variations do not proceed from a universal code analogous to the genomic code. Rather, the primary artifact of sensorimotor behavior refers to a set of processes that include: 1) the coded decomposition of perceptions, which takes into account previous learning; 2) brain processing, which relates new information *in situ* to stored engrams; and 3) the behavioral response and its outcome, which induces eventual adaptation of stored elements.

### *3.2 Caenorhabditis elegans: habituation with twenty neurons*

Starting from the simplest to highlight the most complex is a strategy widely used in science. Many researchers have taken this path, focusing on relatively "simple" animals such as the aplysia, the zebrafish or the drosophila. A few research results concerning the small worm *Caenorhabditis elegans* will suffice here to give an idea of the complexity of a learning process that is considered to be a basic one. With its 302 neurons (118 distinct types) and a lifespan of about 20 days, this small worm learns very quickly to stop reacting to harmless stimuli (habituation); moreover, it is also capable of associative learning of variable duration.

*Habituation* is a universal form of non-associative learning which is of extreme importance since it allows the subject to ignore neutral stimuli in order to concentrate on vital stimuli. Its dysfunctions are related to diseases

(Kepler et al., 2020; McDiarmid et al., 2020). It was first attributed, somewhat trivially, to a depression of excitatory neurotransmission and/or an increase in inhibitory neurotransmission. Current research has been drawing a much more sophisticated picture, highlighting a plurality of habituations mobilizing variable neural mechanisms depending on the nature of the stimuli and the situation.

The habituation to tapping on a *C. elegans* petri dish, even if it passes through the same very limited network of about twenty neurons, solicit synapses, their neurotransmitters and their receptors differently, depending on the rhythm and force of the tapping, the proximity of food or aversive products, the diversity of stimuli during development, and probably on hunger, age, circadian rhythms, etc. The duration, frequency and speed of habituation mobilize different genes. In brief, habituation is multiple and proceeds from equally multiple mechanisms. This learning, presumed to be the simplest and most basic in life, takes complex paths, combining with multisensory perceptions and processing including proprioception (Ardiel et al., 2017; McDiarmid et al., 2019; Gourgou et al., 2021). These links apparently increase plasticity and adaptability.

In short, research on this small worm, half of whose 19'000 genes are found among the 23'000 genes in human DNA, tells us that: - changes in behavior resulting from experience are the norm in C. elegans; - this plasticity relies on the combination of a few neurons and types of neurons integrated into very limited networks; - though rudimentary, these neural structures suffice to allow for a wide variety of learning possibilities that are disconcertingly complex. Work on aplysia and zebrafish leads to similar findings (Randlett et al., 2019).

Sensorimotor learning involves fine-grained and differentiated plasticity. *C. elegans* has only mechanosensory and chemosensory neurons; it lacks sight and hearing. Evidently, the increase in perceptive sources and brain mass multiplies the possible crossings and processings. Learning therefore refers to neural processes of great complexity. Neurosciences are not at the end of their task.

### *3.3 Social learning and culture*

Each species develops itself and creates its world by finding its place in the biosphere. And each individual of each species follows more or less singular experiential paths. It is impossible to relate here even in part such immense neurobiological and behavioral diversity. We refer therefore only to the research on *social learning* and *animal cultures*.

Living beings learn not only from their direct relationships with nature, but also from their interactions with others and, in particular, with their fellow creatures. Social learning is the sensorimotor equivalent of gene transfer in genomic learning. In recent decades, ethologists have discovered that this mode of learning is much more widespread in non-humans than they had first thought. It is now well documented, through observations and experiments in mammals (Thornton & Clutton-Brock, 2011), including primates (Whiten, 2012, 2021; Whiten et al., 2017; Fischer & Hammerschmidt, 2019) and cetaceans (Whitehead & Rendell, 2015; Garland et al., 2017), birds (Fisher & Hinde, 1949; Thorpe, 1951; Marler & Tamura, 1962; Logue & Leca, 2020), fishes (Laland et al., 2011), and insects (Danchin et al., 2018; Bridges & Chittka, 2019; Alem et al., 2016). It takes place in critical areas of activity such as feeding, reproduction, predator avoidance, vocal communication and migrations (Hoppitt & Laland, 2013).

If social learning concerns a relationship with the natural environment, it is at the root of a technical culture. And if it concerns relationships with others, it gives rise to socio-cultural features. Cultural biologists distinguish between degrees of culture. According to Heyes (2020), the first degree, the most basic and widespread, refers to the learning of a behavior by imitation of one or more conspecifics (horizontal transmission). This is for example the case of female grouse, which prefer to mate with males with which they have seen other females mate.

The second degree of culture adds a condition: the behavior must not only be socially learned, but also typical of a group as a whole, as well as rare or absent in other groups of the same species (Laland & Janik, 2006). This requires intergenerational transmission, also known as vertical transmission. Most often, only one behavior per species is involved; however, in chimpanzees, groups studied differed by up to twenty several technical or cultural traits (Boesch et al., 2020).

The third level of culture adds the criterion of accumulation, following a recurrent four-step pattern: behavioral change, diffusion within the group through social learning, improved performance, the entire process serving as the underpinning for another behavioral change, etc. (Mesoudi & Thornton, 2018). The third stage would be typical of human culture and would manifest itself both in the progressive complexification of language and in the combination of tools and manufacturing processes.

Over the past three decades or so, culture, defined as the creation and inheritance of a set of behavioral traditions through social learning (Whiten et al., 1999; Whiten, 2021), has become a major topic of research in ethology, breaking down an age-old wall between the humanities and natural sciences. The *Cultural Evolution Society*, founded in 2015, brings together hundreds of biologists interested in studying cultural dynamics. Some of them specifically examine the effects of cultural transmission on the genetics of populations, with the hope of unveiling gene-culture coevolutions that include cultural selective pressures (Whitehead et al., 2019; Creighton et al., 2021). Social learning opens a new self-artifactual window to the evolution process, that of behavioral convergences achieved through imitation mobilizing sensorimotor capacities. This opening obviously concerns communication.

### *3.4 Culture and communication*

Besides hereditary signals, whose evolution is supposed to be subject to the selective pressure of their own effectiveness, interpersonal, group and symbolic signals (Fröhlich & Van Schaik, 2020) correspond to the three cultural degrees described above. Interpersonal signals, invented and co-learned by two or more subjects, most often proceed from what ethologists have called *ontogenetic ritualization* (Tomasello, 2008): a gesture, a vocalization or a facial expression are, by repetition, associated with a meaning shared by a few relatives. Beyond that, signals learned and shared by a group as a whole have received much attention since the discovery in California in the early 1960s of dialects in a passerine bird, the white-crowned sparrow (Marler & Tamura, 1962). At a distance of about 20 km, the birds' songs differed from each other. This discovery was a bombshell and has generated a great deal of research (Podos & Warren, 2007). Not only can some birds learn variations from a conspecific, or even imitate other species, but social learning can result in vocal subcultures. In humans, symbolic signals or signs, largely arbitrary with respect to their meanings, make dialects both common and inevitable, with the addition of other features that ethologists are trying to find the premises of in non-human animals.

The ability to learn and modify vocalizations, which is very present in songbirds, especially passerines, is rather rare in mammals, with the exception of dolphins, some whales, bats, some primates, and humans (Mathevon, 2021). Learning occurs by listening to acoustic patterns, forming auditory patterns, and then learning to produce vocalizations that match the patterns. This auditory feedback is absent from more limited, highly heritable vocal learnings (Tyack, 2019; Nieder & Mooney, 2019). Songs typically consist of short sound elements (syllables) aligned in exact order and timing. Therefore, the learner must learn to form the individual syllables, ordering them in temporal sequences (Clayton, 2019). This ability may be lifelong or limited in time (Genzel et al., 2019).

Songs signal membership to a particular species or subculture and sometimes denote the identity of the sender (Spillmann et al., 2010); they may also signify that they are directed at singular receivers, such as mating partners or competitors. For example, each bottlenose dolphin (*Tursiops truncatus*) develops its own identity signal that is remembered by others, thus allowing members of a group to name and address each other (Griesser et al., 2018; King & Janik, 2013).

In most cases, only certain elements of a song are changed during intergenerational transmissions (Lachlan et al., 2018). These shifts can be accompanied by geographic shifts and generate dialects that are increasingly distant from each other, to the point where birds no longer recognize each other and pair up (Irwin et al., 2001; Otter et al., 2020). Transformations can be important and rapid, as for example in humpback whales (Noad et al., 2000; Garland et al., 2013, 2017). Change and conformity are not necessarily mutually exclusive, as the propagation of a change requires its conforming expanded reproduction (Whiten et al., 2005). Research is well underway on the causes of these cultural dynamics (Van Schaik, 2012; Garland & McGregor, 2020; Aplin et al., 2015).

### *3.5 Phonetic and syntactic combinations*

By combining a limited number of sounds (phonemes), human language gives rise to a considerable number of words (morphemes), and by combining these syntactically, it opens up a infinite number of sentences. For some theorists, these combinatorial abilities are unique to humans (Chomsky, 1999; Bolhuis et al., 2014, 2018), whereas for others, they are already preformed in non-humans.

Elementary syntactic abilities have, for example, been demonstrated in the alarm calls and long calls of some primates (Crockford & Boesch, 2005; Clarke et al., 2006; Clay & Zuberbühler, 2011; Zuberbühler, 2012; Ouattara et al., 2009; Candiotti et al., 2012; Collier et al., 2020). The same has been observed in some passerines (Townsend et al., 2018; Engesser & Townsend, 2019; Suzuki et al., 2016, 2017; Walsh et al., 2019). The equivalent of our phonemes (meaningless sound units that enter into word formation) has also been spotted in two songs of a passerine bird (Engesser et al., 2016, 2019). For two experts in these matters, the most remarkable animal syntaxes differ from human syntax only in degree of complexity, not in kind (Suzuki & Zuberbühler, 2019).

Lexical and syntactic combinations are related to cognitive abilities. Research on this point includes intentionality, which is considered by Grice (1957) as specific to human language. Yet it is now established that great apes and also some songbirds communicate intentionally (Hage et al., 2013; Townsend et al., 2017; Pennartz et al., 2019; Graham et al., 2019; Heesen et al., 2020; Kabadayi & Osvath, 2017). Other research focuses on categorization abilities, which are essential for constructing words and sentences. As soon as sensorimotor categories are coupled with representations, they are ready for some form of symbolic language. The breaking of nuts by chimpanzees helps to illustrate this. Such an operation requires representation, anticipation and training. It refers to perceptual categories (of more or less skilled subjects, of nuts, of types of anvil and striking stones, of orientation and strength of blows) that are organized into a kind of pre-symbolic syntax of action, ready to accommodate the universal language schema which articulates actors, actions and patients (Fitch, 2019, Ten Cate, 2018).

Languages based on sensorimotor social learning are social artifacts. They open to the self-construction of whole-beings, whose potential explodes with symbolic learning.

### *3.5 In summary...*

Sensorimotor learning is the provider of a fine and rapid adaptive plasticity, based on a concomitant plasticity of neuronal connections. It also opens a window to social learning. Learning from others allows the construction of behavioral convergences, that is to say the first steps of culture, both in the relationship with nature and with others. These cultural whole-beings also concern the communicational dimension, and many ethologists now hypothesize that there is a difference in degree rather in kind between the structure of certain animal languages and the combinatorics of human language.

## **4. Symbolic learning**

Research on social learning and animal cultures underlines the evolutionary continuity between animals, humans and non-humans. The human exception looks less and less like a thunderclap in a sensorimotor sky dedicated to perceptive immediacy and instinctive reactions. In the same way that there is a tight articulation between the genomic and the sensorimotor, there is a close entanglement between the latter and the symbolic. This is not really surprising since symbolic codes appear at the intersection of a double development, that of the sensorimotor capacities – and in particular of the auditory and phonatory – and that of the capacities of representation. Research in child psychology underlines the sensorimotor rooting of the symbolic. The following remarks are limited to the development of language and technique, artifacts that are linked, while hypotheses concerning the neural bases of representation, language and consciousness are left aside.

### *4.1 From sensorimotor social learning to symbolic social learning*

No neural pre-wiring seems to favor the learning of any particular language. All human infants are likely to learn one or more of the 6,000 or so known languages and to master the dozens of phonemes that each one mobilizes out of the 800 known worldwide. While still in their mother's wombs, and later as infants, they become familiar with the sounds, their frequencies and associations (Le Calvez, Pepperkamp & Dupoux, 2007). They register regularities and irregularities of all kinds (Rochat, 2004); their neural networks are formed as they become imbued with the sensory features of their language and its corresponding social and natural environment.

It is on this basis that the symbolic takes root. Initially, representations are attached to perceptive categories: objects continue to exist even if the child does not perceive them. This acquisition of object permanence is progressive and can be broken down into several stages shared to varying degrees by many animal species (Piaget 1954, Baillargeon et al., 1985). Little by little, a representational world is formed above the perceptual categories. Over time, the child learns to associate acoustic images with the representations of objects, i.e. to understand and formulate signs. He is then confronted by a great challenge, that of articulating two worlds, a representational world whose existence is manifested at will by language, and a world of practical effectuation which is profoundly transformed. In the first world, virtual reversibility reigns (we can move freely in time and space, transfigure our motor and perceptive capacities, etc.), whereas the second is heavily marked by irreversibility (even if we can sometimes repair a broken pot, it is impossible to erase the event that took place). This duality, which is the starting point of a later differentiation of social worlds, is likely to feed both inventiveness and instability that may contradict the dominant norms and rules of a given cultural community. In order to transmit and regulate these fragile whole-beings composed of several worlds, social learning is no longer sufficient: educational support is necessary.

### *4.2 Teaching*

Among our animal friends, social learning is central, whereas education is the poor relative. In order to identify the prefigurations of educational relationships in animals, Caro and Hauser (1992, 153) have proposed an objectivist definition of teaching, thus bypassing the dimension of intentionality that remains difficult to establish. For these authors, an actor A teaches – by encouraging, punishing, providing an experience or offering an example – “if he modifies his behavior only in the presence of a naïve observer, B [the student], at some cost or at least without obtaining an immediate benefit for himself”.

Other researchers (Hoppitt et al., 2008; Hoppitt & Laland, 2013) suggest that teaching postures build on and exceed *inadvertent social learning*, in which the model acts in pursuit of its own ends, without regard for potential learners who may be inspired by them. The teaching dimension can modify this "pure" social learning in several ways:

- rather than being followed by chance when moving to a site of interest, the possessor of knowledge can ensure that it/he is followed by a naïve subject or subjects (in *Temnothorax albipenni* ants, tandems are thus observed where an informed subject leads a naïve subject to a food source, thus inducing learning) (Franks & Richardson, 2006); the dance of bees, which transforms ignorant bystanders into informed subjects of an interesting food location, seems to belong to the same category, a mix of genetically recorded mechanisms and induced learning;
- rather than being inadvertently exposed to a relationship between two stimuli, the learner may be introduced to such a relationship through repetitions (blackbirds exposing chicks to the relationship between one type of call, the "purr" call, and food);
- rather than simply being observed performing an action and subsequently imitated, the subject who is the repository of the skill may set itself up as a demonstrator (a bird singing longer than usual in front of an apprentice) (Beecher & Akçay, 2020; Taylor, 2021);
- rather than unknowingly providing a learning opportunity, tutors can tailor their products to theirs students' learning capacities (meerkats, cats and cheetahs bring prey that is sometimes dead, sometimes injured, and sometimes intact back to their cubs, depending on the age of the young, thus providing opportunities for them to exercise their hunting dispositions).

In short, inadvertent social learning appears to be the first stage of cultural transmission, with educational behaviors reducing inadvertence and increasing the chances of transmission. The human species has progressively increased the educational pole as cultural diversity and arbitrariness have developed. The socio-cognitive complexity of learning has also increased in understanding and guidance (Bandura, 1977). The decisive mutation comes from language, a formidable tool of transmission of the technical, political and cultural assets. The characteristics of the sign help to understand the extent of the issues at stake.

### *4.3 Symbolic codes, learning and education*

The arbitrariness of the sign opens up an indefinite number of possible languages, each with its own code and its own way of articulating concepts (signifieds) and acoustic images (signifiers). Signs are based on socially shared mental representations; they are therefore subject to norms of use that are imposed during learning. These norms concern the lexicon as well as the syntactic rules and their numerous exceptions.

This normative dimension is reinforced by the fact that the sign is not bound to its external "real" referent (the object or set of objects designated by the sign), thus creating the possibility of erroneous or deliberately distorted, even deceptive, constructions of reality. It follows that socially shared meanings are indissolubly linked to the virtuality of non-sharing. Such a situation threatens communication and calls for a set of regulations that must be transmitted to keep it within acceptable limits.

As the sign is not indissolubly linked to a real referent, it allows : - to lie; - to invent imaginary fictional referents; - to create sacred mythical referents; - to conceive legendary or utopian referents. It thus leads to plural worlds, forming symbolic universes specific to each culture. Learning to navigate in this plurality of worlds is not easy: children have difficulty in distinguishing and navigating between reality, representation, fiction, lies, truth, myth and utopia; multiple learning and interpretative uncertainties continue throughout life.

Languages are neither stable nor homogeneous. They manifest a permanent heterogeneity in the form of lexical and syntactic variations, dialects, accents, expressions, networks of meanings. This heterogeneity can be accentuated by geography, regional autonomy, the density of exchanges, the division of labor and social classes. Normative tensions around language thus tend to affect all exchanges.

Finally, in symbolic societies, the signifier-signified relationship tends to extend to all perceptible objects and behaviors to which the actors give specific meanings. Everything becomes a potential sign: social position, sex, race, wealth, profession, clothing, food, habitat, etc. Linguistics extends into semiotics. And from there, the differences and normative tensions extend to the entire society, structuring social relations and social distinctions. The processes of individuation present at the genomic and sensorimotor levels receive a new impulse, the symbolic identity being able to vary during the course of life, sometimes in spectacular ways.

Language associated to symbolic representation, constitutes the *artefact princeps* from which proceed: the multiple languages and cultures within the only human species, the different social worlds within each culture, the systematic guidance of the social learning and the omnipresent normative regulations. The external proliferation of technical instruments also seems to be linked to these developments.

### *4.4 Instrumental externalization and learning*

Starting with Darwin himself, the hypothesis of evolutionary connections between language, gesture and tools has been proposed and defended on numerous occasions (Leroi-Gourhan, 1943; Stout & Chaminade, 2012), as the combinatorics of language and of tools may proceed from similar, or even common, mechanisms. The question remains open, reinforced by the existence of a pre-symbolic syntax of action in terms of actors, actions, and patients, reinforced also by neuroscientific research that has uncovered significant neural overlaps between practical actions and language expressions which designate them (Boulenger, 2006; Thibault et al., 2021; Osiurak et al., 2021). Moreover, the effort to produce compliant songs or signifiers, that is, artifacts in terms of sound waves, is not unlike the effort to produce concrete artifacts.

Let's go back to the example of breaking nuts or stones. To crack nuts, chimpanzees combine two external objects assigned to the role of tools, a stone that acts as a hammer and another that serves as an anvil. To break stones, *Sapajus libidinosus* and and *Macaca fascicularis* monkeys combine a stone acting as a hammer and another stone intended to be struck to obtain a number of tool-chips (Proffitt et al., 2016, 2023; Falótico et al., 2019). In both cases, we can speak of duplication of instrumental externalization. The stone assigned to the role of tool is an intelligent externalization in an object separated from the body. This object is integrated by the actor in the anticipated unfolding of a transformative action (breaking the nut, obtaining a chip), in other words, in an embodied syntax of the action. The intelligent processes of incorporation (representations and acquired skills) and externalization (execution) of the action are correlative to each other. The chimpanzee's aim and gestures must impart sufficient force to the stone to overcome the resistance of the nut. The behavioral information of the living can then be seen as imposing itself on the information of the non-living, thanks to a technical mediation.

Carved stone, which implies knowledge of the materials and learned skills, is the best marker of early humanity that we dispose of. The oldest specimens discovered are 3.4 million years old and are notably attributed to Australopithecines (Harmand S. et al., 2015). When our ancestor attaches a carved stone to a wooden handle to make a carved stone axe, we can say that he is joining two action phrases to form a technical mini-text. Articulating two artifact-tools suggests the birth of a technical reflexivity that stimulates inventions and their reciprocal combinations. Inventions, combinations and transmissions are at the core of the logic of accumulation.

If the tool is composite, several specialized craftsmen can make the various components separately. The different knowledge and skills involved can thus be subdivided. On the other hand, using a tool skillfully does not necessarily mean mastering its manufacture. A second division of labor, with its correlative learning, which will intensify with the proliferation of tools, can thus be established. From then on, it is no longer enough to think of the processes of incorporation/externalization on an individual scale, but to consider their distribution on the collective scale of a society.

### *4.5 The machine*

Already present in Antiquity, the mill is one of the first machines resulting from human engineering. It assigns to the tool a stable mechanical functioning that no longer needs the hand to accomplish what is expected of it (the crushing of grain, a physical information). The sensorimotor and symbolic information is externalized in the mechanism of the mill. Later, the replacement of energy of biological origin by energy of physical origin, will allow to obtain an automatic machine. Learning the correct grinding gesture becomes obsolete; it is replaced by learning how to build the mill and to maintain it.

Let us take a leap forward: the punched cards of the Jacquard loom are the ancestors of digital algorithms, because, thanks to a binary code (one hole = raised warp thread, no hole = untouched warp thread), they allow to weave a large variety of complex patterns without the intervention of the weaver. A coded knowledge in punched cardboard, a symbolic artifact – the primitive ancestor of the computer – has replaced the weaver's knowledge and drives the machine.

## 5. Conclusions: the technical epiphany and learning

Learning by self-transformation at the molecular level becomes possible with the genetic code. Learning by self-constructing multiple sensory and motor worlds according to species becomes possible with neural codes. With the emergence of symbolic codes and languages, learning by deploying a plurality of cultures within the same species and a plurality of worlds within each culture becomes the norm. These different types of learning, in the sense of the evolutionary self-construction of a species, are associated with individual and social learning, sometimes through mutations, drifts and transfers, sometimes through behavioral variations or symbolic constructions. In a similar way to physics, which must reconcile the properties of particles and the evolution of the universe, the life sciences, from biology to sociology, must constantly re-articulate individual and collective dynamics.

From the cellular manufacturing of proteins guided by genes (more precisely messenger RNAs derived from genes) to the manufacturing of objects guided by digital algorithms, it is possible to speak of a technical epiphany marked by successive emergences. The concept of emergence applies to evolutionary processes characterized by continuities and ruptures, and in particular by the irreducibility of new dynamics to old ones. This anti-reductionist vision is partly hypothetical and subject to debate, since we must acknowledge that knowledge of the transitional processes that have accompanied each stage remains partial.

Reflecting upon learning today requires a re-evaluation, in the sense of concepts that are sufficiently broad to encompass the living world as a whole and sufficiently differentiable to reflect the new dynamics that have marked its unfolding. The concepts of information, algorithm and artefact outlined above meet this requirement. Their extension implies that of the concepts of technique and of learning. Contrary to the elements that compose the physical-chemical, which only associate under certain physical conditions, all living beings manufacture and learn. It is therefore necessary to pay great attention to the rupture between the living and the non-living: - to the difference between physical information and information in the sense of biological knowledge; - to the difference between physical morphogenesis and morphogenesis of the living, the latter producing artefacts according to need, by mobilizing and adapting knowledge, notably in algorithmic form. For each level of learning, information, algorithm and artefact receive new determinations and open up new horizons. This said, the present text remains fragmentary, its goal being to present a line of reflection.

The digital revolution is part of the technical epiphany of the living. With its own algorithmic tools, it guides automated processes, ensures and analyzes continuous flows of information, weakens or reinforces control and regulation devices, opens up the translation of the whole *in vivo* into *in silico,* and finally affects the morphogenesis of individual and collective subjects. A new global learning dynamic is emerging, which will probably cause another rupture in the evolution of the human species and its relationship with the living and the non-living.

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