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Principles of cognitive biology and the concept of biocivilisations

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ABSTRACT

A range of studies published in the last few decades promotes the cognitive aspects of life: all organisms, from bacteria to mammals, are capable of sensing/perception, decision-making, problem-solving, learning, and other cognitive functions, including sentience and consciousness. In this paper I present a scientific and philosophical synthesis of these studies, leading to an integrated view of cognitive biology. This view is expressed through the four principles applicable to all living systems: (1) sentience and consciousness, (2) autopoiesis, (3) free energy principle and relational biology, and (4) cognitive repertoire. The principles are circular, and they reinforce themselves. The circularity is not rigid, meaning that hierarchical and heterarchical shifts are widespread in the biosphere. The above principles emerged at the dawn of life, with the first cells, bacteria and archaea. All biogenic forms and functions that emerged since then can be traced to the first cells – indivisible units of biological agency. Following these principles, I developed the concept of *biocivilisations* to explain various forms of social intelligence in different kingdoms of life. The term *biociviloisations* draws on the human interpretation of the concept of civilisation, which searches for non-human equivalents of communication, engineering, science, medicine, art, and agriculture, in all kingdoms of life by applying the principles of cognitive biology. Potential avenues for testing the concept of *biocivilisations* are highlighted.

1. Introduction

Humanities and sciences often interpret the world differently. For example, the education system promotes the anthropocentric view that history started ~5000 years ago with the invention of written language as the method for recording events (Stearns et al., 2000; Robinson, 2007). Human societies living before the invention are usually considered less advanced than their post-written-language counterparts even though they possessed authentic cultures (Feyerabend, 2016, p7). On the other hand, the recording of events in the natural world is integrated into the forms and functions of organisms through varieties of biological memory. For example, by analysing DNA the entire repertoire of living forms that emerged in the four-billion-year evolutionary history is classified neatly into three domains of life (Woese et al., 1990). From the naturalist perspective division of societies into modern and primitive varieties is an artifact of the human interpretation of the world.

However, humanities and sciences occasionally take similar positions. This convergence of opinions, often unintended, opens the route for reconciling differences. A historian Niall Ferguson (2011, p3) remarked “Civilizations are partly a practical response by human populations to their environments – the challenges of feeding, watering, sheltering and defending themselves.” Even though Ferguson did not intend to reconcile naturalist and humanist versions of history, his description of civilisations opens an interesting prospect. If the word “human” in the above quote is replaced by “bacterial”, “protist”, “fungal”, “plant” or “animal”, it turns out that the meaning of the term civilisation acquires a naturalist perspective that goes beyond the conventional interpretation.

Ferguson’s remark resonates reasonably well with the basic principles of life sciences. There is a clear distinction between organisms (human populations), environments, and how organisms deal with existential challenges emanating from their interactions with the environments (feeding, watering, sheltering, and defending). As a historian, Ferguson placed the human methodology for dealing with existential challenges under the umbrella covered by the term civilisation. The traditional meaning of the term conforms to the version of history constrained by the human perspective of existence (see above) and refreshed by the more recent experiences of European culture. For example, the term civilisation originated from the French language. It was dated to the 17th century and it represented the antonym for barbarism (Ferguson 2011). The preferred English term was civility, which means polite urban behaviour (Ferguson 2011). The contemporary globalised civilisation, according to Ferguson, dominated by six achievements of modernity that spread around the world – competition,

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science, property ownership, medicine, consumerism, and work ethic – is the epitome of the human collective intelligence that now dominates the entire natural world. There are similarities between Ferguson's scenario and the concept of Anthropocene – a putative new geological epoch that places *Homo sapiens* at the apex (Steffen et al., 2011; Lewis and Maslin, 2015) – effectively summarised in a leading scientific journal: "… humans have replaced nature as the dominant environmental force on Earth" (Ruddiman et al., 2015).

However, the above interpretation of the term civilisation – domination of human intelligence over the biosphere – is challenged by an emerging cognitivist interpretation of biology that views (i) organisms, from bacteria to mammals, as intelligent natural agents capable of anticipation, learning, and problem-solving (Bateson, 1979; Rosen, 1985, 1991; Capra and Luisi, 2016; Nicholson and Dupré, 2018) and (ii) the biosphere as the system integrating all its components (organisms and environments) in the ever-changing trajectory of evolution (Rubin et al., 2021). The cognitivist programme expanded recently through a series of ground-breaking studies (Lyon, 2015, 2017; Reber, 1997, 2019; Reber and Baluška, 2020; Reber et al., 2023; Baluška, 2010; Baluška et al., 2016, 2022, 2023; Baluška and Reber, 2020; Miller et al., 2020; Miller et al., 2021, 2023; Miller, 2023). A panoply of terms is used to describe this new position: a bacterial cognitive toolkit (Lyon, 2015), natural genetic engineering (Shapiro, 2011), honeybee democracy (Seeley, 2010), bacterial IQ (Galperin, 2005), bacterial urbanisation (Paula et al., 2020), bacterial linguistics (Ben Jacob et al., 2004), plant language (Holopainen and Blande, 2012), plant intelligence (Trewavas, 2017) to mention a few.

According to this emerging body of research each species has its own perceptual or cognitive space that may be broadly summarised as a form of naturalist civilisation if we adopt Ferguson's description, and expand it to non-human species. To formalise this naturalist scenario I coined the term biocivilisations, which means that each species interacts with its environment cognitively, and in the process, it changes the environment in line with the rules of its own cognitive space (Slijepcevic, 2023). Those rules are described by various disciplines including biosemiotics, relational biology, the systems view of life, and evolutionary epistemology (reviewed in Slijepcevic 2018, 2020, 2021). The total of a species-specific cognitive interaction with its environments, and subsequent environmental changes, is the emergence of the new morphological space within the biosphere – a new biocivilisation – that seamlessly integrates into the continuum of biocivilisations and it contributes to the functioning of the biosphere as the planetary-scale system (Slijepcevic 2023).

This paper aims to outline the concept of biocivilisations introduced in my earlier papers (Slijepcevic 2020, 2021) and developed in a recent book (Slijepcevic 2023). The paper is structured in the following way. In section 2, I shall introduce a vision of the science of life dominated by cognition as a biological universal. In section 3, I shall describe three principles behind the concept of biocivilisations that build on the principles of cognitive biology. In section 4, I shall focus on the hallmarks of social intelligence, all rooted in the cognitive capacities of cells, and shared by all kingdoms of life. In the final section, I shall discuss how the concept of biocivilisations can be turned into a formal scientific theory.

2. Cognitive biology

Cognitivist interpretation of biology is not a recent development. Ever since science emerged in the modern form, there was a tension between the mechanical interpretation of life elaborated by René Descartes that paved the way for the mind-body dualism (see, for example, Margulis and Sagan, 1997), and a cognitivist interpretation initiated by Immanuel Kant according to which an organism is not a dual entity but 'a cause and effect of itself' (Kant, 1790, 371).

The cartesian outlook is exemplified by the concept of Modern Synthesis (MS) also known as neo-Darwinism. MS merges Darwin's theory of evolution by natural selection with genetics. According to MS, biological novelty emerges through a simple scenario. Novel gene mutations, or changes in gene frequencies, are responsible for biological variations subsequently favoured by certain environmental features in the process of natural selection (Futuyma, 1998). This almost mechanical scenario (organisms adapt to fixed environments) complements the reductionist outlook of molecular biology and genetics according to which (i) organisms are complex biological machines (Rosen, 1991) and (ii) biology is fully reducible to physics (Elsasser, 1998). Thus, MS and mechanistic thinking in biology keep the cartesian outlook alive. This position is best summarised by Richard Dawkins (1976) in his influential book *The Selfish Gene*. "We are survival machines – robot vehicles blindly programmed to preserve the selfish molecules known as genes. This is a truth which still fills me with astonishment." As a result of the dominant cartesian outlook, non-biologists usually take the above scenario for granted rarely considering alternatives. However, the principles behind MS are refuted, among others, by Shapiro (2011) and Noble (2013) in the contexts of evolution and physiology respectively. Furthermore, the mechanistic basis of biology is refuted by the work of theoretical biologist Robert Rosen (1991), and other proponents of the school of relational biology (Elsasser, 1998).

The Kantian perspective, on the other hand, has only recently started gaining traction with a significant number of biologists (see below). In this paper, I shall call the Kantian perspective "cognitive biology" or CB.[1] Immanuel Kant outlined a distinction between physics and biology in the following way:

> *In my view, we could say here with certain understanding and without presumption: Give me the material, and I will build a world out of it …. However, can we boast of such advantages for the smallest plants or insects. Are we in a position to say, give me the material, I will show you how a caterpillar could have developed? Do we not remain here at the bottom rung because of our ignorance of the true inner constitution of the object and of the development inherent in its multiple elements. Thus, people must not let themselves be disconcerted when I venture to say that we will be able to understand the development of all the cosmic bodies, the causes of their movements, in short, the origin of the entire present arrangement of the planetary system, before we completely and clearly understand the development of a single plant or caterpillar on mechanical principles.* (Kant, 1755, p17-18).

The originality of Kant's thinking resonates with the views of some contemporary scientists. For example, a leading astrophysicist published an essay entitled "Black holes are simpler than forests and science has its limits" (Rees, 2017). A detailed elaboration of the principles behind sciences, including biology, was presented in Kant, (1790) third critique known as *Critique of Judgement*. Kant discussed the distinction between physics and biology by focusing on the concept of teleology. Using persuasive arguments Kant concluded that the mechanistic interpretation of biology may not be ultimately productive. To understand life, science requires an intellectual "toolkit" that goes beyond the

[1] It is important to highlight different interpretations of cognition in the context of life sciences. A critical assessment of biological theories of cognition has been presented by Rubin (2017), including terminological differences between them. For example, the term "biology of cognition" is usually associated with the pioneering work of Humberto Maturana and his collaboration with Francisco Varela (Maturana and Varela, 1980, 1987), from which other collaborations (Mpodozis, 2022) and interpretations (Capra, 2022) developed. On the other hand, the term "cognitive biology" is usually linked to developments in cognitive sciences and subsequent integration with life sciences (Lyon et al., 2021). My CB perspective attempts to integrate different views represented by the above terms, as it will become clear later in the text. It is also important to place the Kantian perspective into a broader context. Samir Okasha (2023) suggested that the Kantian position has precedence in Aristotle's philosophy. In line with this suggestion, Robert Rosen (1991) used Aristotle's four causes to show that organisms are "causes of themselves". Igamberdiev (2023) argued that the code concept in biology was founded by Aristotle.

mechanical principles of physics (Kauffman 2019).

The first prominent biologist who followed Kant's line of thought was Lamarck who gave precedence to organisms as independent entities rather than to mechanical factors that influence the non-living world. Lamarck's idea of inheritance of acquired characters was wrong in the context of multicellular organisms such as plants and animals. However, Goldenfeld and Woese (2007) argued that inheritance of acquired characters, through horizontal gene transfer (HGT) is common in the two domains of life, archaea and bacteria, that preceded eukaryotes by at least two billion years. In addition, Conrad Hal Waddington's experiments with Drosophila in the 1950s led him to propose the hypothesis of "genetic assimilation", which was an attempt to interpret the inheritance of acquired characters in the Darwinian context (Waddington, 1959). More recent research gives credence to the view that acquired characters can be inherited in animals (reviewed in Cabej, 2021) leading to a wider interest in epigenetics. Another aspect of 19th-century biology, the idea of symbiosis (it means living together), was naturally in line with CB because the explanatory principle behind it was the cooperation between organisms of different evolutionary origins, a process that required some form of natural learning (Gontier, 2016). The idea of symbiosis was considered wrong, or even pseudo-scientific, for over a century (see for example, Carrapico, 2015) until Lynn Margulis (then Sagan) published her seminal paper "On the origin of mitosing cell" (Sagan, 1967).

Several developments in 20th-century biology strengthened the CB perspective. These included cybernetics, the general systems theory, biosemiotics, relational biology, and evolutionary epistemology (reviewed in Slijepcevic, 2020). Even though these were disparate fields of research, they shared one important feature. They all interpreted organisms as independent agents thus establishing the link with the Kantian principle that an organism is a "cause and effect of itself". For example, Jakob von Uexküll van, (2010) argued that each animal species has its own "self-centred world" or *Umwelt* in German, an idea that can be interpreted to mean that each species has its own cognitive space that facilitates functions such as sensing, perception, communication, etc.

One of the first scientists who addressed the peculiarity of biological (living) systems relative to physical (non-living) systems was Ervin Bauer (1920, 1982). His main argument was that mathematics can be used to separate biological phenomena from physical ones (reviewed in Brauckmann, 2000). The new mathematics-based explanation of biological systems can in turn disprove the validity of vitalism and mechanism in the context of biology. Bauer depicted biological systems as autonomous self-organising systems that separate themselves from the environment, through specific thermodynamic processes, but at the same time remain energetically coupled with the environment. In this organism-environment coupling, dictated by the organismal internal structure, organisms exploit the free energy from the environment to maintain themselves (self-maintenance, reproduction and variability). Thus organisms "work" against equilibrium that results from the laws of physics, which makes them distinct from machines – man-made devices that do not "work" against the equilibrium (Bauer 1920, 1982; Brauckmann, 2000). Organisms are systems that maintain themselves in a non-equilibrium state. Works of other scientists, from systems theorists (Bertalanffy, 1968) and chemists interested in living systems (Prigogine, 1980) to modern day biochemists (Kauffman, 2019), conform to the ideas elaborated by Bauer.

In line with Bauer's pioneering work, the autopoiesis concept of Maturana and Varela (1980, 1987) formalised the Kantian assumption by arguing that the causal chain of events remains within the organism. The autopoiesis concept is explicit in understanding cognition: "… to live is to know" (Maturana and Varela 1987, 174). Cognition is understood not as a representation of the independently existing world, but as the process of continually "bringing forth a world" (Maturana and Varela, 1987, 26) through the structural coupling of organisms and their environments (Rubin, 2017; Capra, 2022; Mpodozis, 2022). This structural coupling is best understood as a process of organismal structural changes in response to environmental influences. The environment does not determine organismal changes – organisms determine changes in a self-organising way. The constant structural changes within organisms, prompted by environmental influences, but guided by organismal internal structures, represent the process of learning. This process is not confined to organisms with brains, but it is an essential feature of all living systems.

The mathematical elaboration of causation that typifies organisms, as opposed to mechanical systems such as machines, was developed by Robert Rosen (1991) who used the category theory to show that organisms remain closed to efficient causation. Rosen (1985) has also shown that organisms are anticipatory systems capable of producing internal predictive models of themselves and their environments, thus providing an indirect link with Bauer's pioneering work, but also a direct link with the concept of autopoiesis by giving it the mathematical foundations.

The most recent development that unifies scientific principles behind CB is the elaboration of the free energy principle, Markov blankets and active inference. These features are unique to living systems, from cells to the biosphere (Friston et al., 2006; Rubin, 2017; Rubin et al., 2020). The free energy principle, in the context of the organism (system 1) – environment (system 2) interactions, is a statistical measure (probability) of the environmental quantities that act on the organism and distribution of these quantities encoded by the organism's internal structure (Friston et al., 2006). It can be stated that the organism minimizes the free energy, through changing its own configuration within the homeostatic bounds, to maximize the optimal sampling of the environment (perception). By doing so the organism preserves the internal configuration (distribution of its own states within the homeostatic boundary). Markov blankets define the separation of the organism form the environment, while active inference refers to the process of the organism-environment interactions (Kirchhoff et al., 2018).

In parallel with the philosophical and mathematical elaborations of CB principles, there were innovative efforts to redefine the theoretical basis of biology. Gregory Bateson (1979) argued that interactions between organisms and environments are based on cognitive principles, leading him to propose the concept of the natural mind that can be tested by applying six criteria. Other developments followed including (i) biosemiotics, which relied on Uexküll's work to study meaning-making processes and communication in the living world (Sebeok, 2001), and (ii) evolutionary epistemology which initially used neo-Darwinian principles to study cognition but later incorporated other angles including symbiosis (Slijepcevic, 2018).

Research centred around CB principles intensified in the last several years. Arthur Reber, William B. Miller Jr., and František Baluška proposed theories such as Cell-Based Consciousness (CBC) and Cognition Based Evolution (CBE) (Reber et al., 2023; Miller, 2023). Theme issues of various journals explored the principles behind CB (see, for example, Lyon et al., 2021). Finally, CB principles have been explored from the angles of systems biology (Capra and Luisi, 2016) and processual biology (Nicholson and Dupré, 2018).

Taking all the above arguments together, the most succinct summary of CB may be expressed as follows. Organisms, from single-cell prokaryotes to most complex multicellular eukaryotes such as plants and animals, are independent agents capable of sensing/perception, decision-making, problem-solving, learning, anticipation, communication, and other functions required for cognition including sentience and consciousness (Lyon et al., 2021; Reber et al., 2023). Basic and indivisible units of agency are cells (Baluška et al., 2023; Reber et al., 2023); genes and genomes as subordinate "organs" of cells. The agency represents a dynamic whole maintained by the active synergy of its parts (Capra and Luisi, 2016). The MS position that evolution is driven purely by gene mutations, gene frequencies, or genetic drift, unwittingly removes cells from the chain of causation. However, CB in general, and CBC/CBE in particular, rectify this error and argue that cognition based on cells is a biological universal (Miller 2016, 2023; Reber et al., 2023).

CB integrates smoothly with the continuity principle of evolution. This principle is summarised by Baluška et al. (2023): "the *de novo* formation of cells is not possible; all present cells are products of other prior cells" building on the 19th-century cell theory of Schleiden, Schwann, and Remak summarised in the Latin phrase *Omnis cellula e cellula* coined by Rudolf Virchow. This means that biological forms and functions have a common origin that goes to the point in our planetary history when life emerged in the form of the first prokaryotic cells, bacteria and archaea, from which all other life forms emerged. For example, the origin of vision, as an important organismal function, can be traced to the so-called "bacterial eye" and the principle of phototaxis (Scuergers et al., 2016). Vision in animals and other organisms is derived from this primordial bacterial cellular function (Nilsson and Colley, 2016). By analogy, cognition, as a wider function that integrates many other organismal functions, from sensing the environment to anticipation and decision-making, can equally be traced to first cells reaffirming the notion that cells are indivisible units of agency, sentience, and cognition (Baluška et al., 2023; Reber et al., 2023). Even though this is not yet a widely accepted notion many researchers subscribe to it. For example, Capra (2022) coined the term "cellular autopoiesis". Furthermore, an effective summary of this position was articulated by Pamela Lyon (2023) at the Luskin Symposium, Pushing the Boundaries: Neuroscience, Cognition, and Life, held at UCLA on 26th and June 27, 2023, in her take-home message: "Alignment connects cognition in bacteria with cognition in animals with nervous system + supports the notion of a continuum of cognitive function from simple to complex".

A summary of CB principles is presented in Fig. 1. The summary integrates all mathematical and theoretical elaborations discussed in this section. The starting assumption (principle 1) is that all organisms, from bacteria to plants and animals, are sentient and conscious (Fig. 1 A). Sentience and consciousness are the consequence of autopoiesis (principle 2) (Fig. 1 A). Autopoiesis means that organisms fabricate themselves – the chain of causation remains within organisms. As a result of autopoiesis, organisms separate themselves from the environment (Markov blankets) and engage in active inference by minimizing free energy to maximize the persistence of their internal structures within homeostatic bounds (principle 3; combination of free energy principle and relational biology of Robert Rosen) (Fig. 1 A). The result of principles 1–3 is the emergence of the species-specific cognitive repertoire (principle 4) (Fig. 1 A). The four principles are linked into a circle – they reinforce themselves.

However, the circularity is not rigid: shifts from one level of hierarchy to the next may occur. For example, prokaryotic cells complexify into eukaryotic cells – a hierarchical shift that falls within the category of major evolutionary transitions (West et al., 2015). An elaboration of CB principles that takes account of major evolutionary transitions from the perspective of cells, is presented in Fig. 1 B. These evolutionary transitions include (i) eukaryogenesis (1^e-4^e in Fig. 1 B) and (ii) multicellularity (1^m–4^m in Fig. 1 B). As a result of major evolutionary transitions, cognition manifests differently at different levels of "cellular autopoiesis" (Capra 2022). Yet, the four principles remain operational at all levels of biological hierarchy thus reflecting (i) the network organisation of the biosphere and (ii) its nested structure incorporating various levels of organisation starting with first cells (Fig. 1 B). The network pattern, however, also implies the emergence of heterarchy: living systems considered hierarchically lower (e.g. bacteria) may exert influence on living systems considered hierarchically higher (e.g. animals) by acting as the interface between the multicellular body and the environment, whereby microbiomes turn animal bodies into holobionts (Simon et al., 2019) (Fig. 1 B).

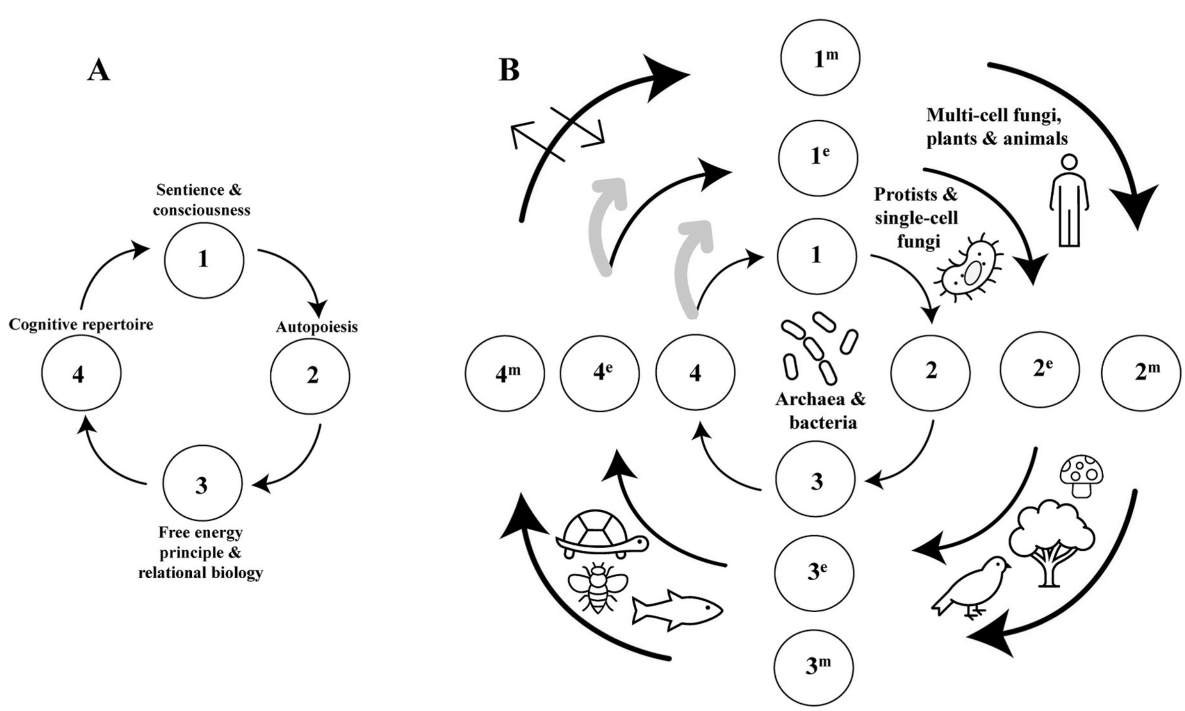

Fig. 1. A. Principles behind CB (for details see the text). B. CB principles in the context of cell biology. Two major evolutionary transitions involving cells include eukaryogenesis and the emergence of multicellularity. In this context, there are three levels of cellular hierarchy to which CB principles equally apply: simplest prokaryotic cells, bacteria and archaea (principles 1–4); single-cell organisms emerging after the first major evolutionary transition (eukaryogenesis), protists and single-cell fungi (principles 1^e-4^e) (e is for eukaryoegensis); multicellular organisms emerging from the second major evolutionary transition (multicellularity), multicellular fungi, plants and animals (principles 1^m–4^m) (m is for multicellularity). Grey curved arrows represent major evolutionary transitions, or hierarchical shifts. Double black arrows, oriented in different directions, represent heterarchical shifts. Details behind the concept of heterarchy are presented in Section 5 (Discussion). In brief, the hierarchical order may be represented as A → B → C. In a heterarchical order orientation C → A → B, or any other configuration is possible. Hierarchy and heterarchy are not mutually exclusive.

In summary, this section provides a historical overview of cognitive theories in the context of life sciences, and it outlines an integration of these theories by combining key philosophical (e.g. the Kantian perspective) and scientific arguments (from Ervin Bauer to modern developments) (see Fig. 1).

3. Principles behind the concept of biocivilisations

My concept of biocivilisations builds on the grounds established by CB. It is guided by three principles which will be outlined in this section. These include critique of anthropocentrism, social intelligence, and convergent evolution.

3.1. *Critique of anthropocentrism*

The critique of anthropocentrism (Fig. 2) is depicted as a representation of timelines of organismal forms in the history of life, or in the course of evolution. The timeline has a form of the Gaussian curve (normal distribution) combined with the three-sigma rule (or the 68-95-99.7 rule). The three-sigma rule is a useful heuristic in empirical sciences (Grafarend, 2006). One sigma (σ) represents one standard deviation from the mean. According to this rule, nearly all values are located within three sigmas or three standard deviations from the mean. The practical consequence of the three-sigma rule is that the 99.7% probability is equivalent to 100% – any value located outside the three-sigma is a non-representative outlier.

Given that the position of *Homo sapiens* on the curve of life is equivalent to a non-representative outlier (Fig. 2), while bacteria, archaea, protists, fungi, plants and many animal species have clear imprints on the curve, the assumption of many scientists from various fields that "… humans have replaced nature as the dominant environmental force on Earth" (Ruddiman et al., 2015) lacks credibility when the evolutionary scale is used as the basis for making system-level predictions, whereby the biosphere in its entirety – temporal as well as spatial – is the system of interest. By the same token, assuming that human cognition is a form of ultimate cognition that should serve as a measure for all other cognitive forms lacks system-level credibility. This problem is recognised by the phrase coined by Anthony Trewavas (2017), "brain chauvinism", to support the view that plants, which constitute 75% of the biosphere by biomass (Bar-On et al., 2018), and have a clear imprint on the curve of life (Fig. 2), lack the brain and yet do have cognitive capacities. Arguably, the cognitive capacities of plants are responsible for the long-term ecological resilience of forest biomes that go far beyond human capacities (Sheffer et al., 2015). Furthermore, James A. Shapiro (2007) argued that bacteria, the second major contributor to the biosphere's biomass after plants, with a 20% share (Bar-On et al., 2018), have astonishing geoengineering capacities superior to human capacities. The practical consequence of Fig. 2 is the inevitable shift from human-centred cognition to cognition as an evolutionary and biosphere-wide universal.

3.2. *Social intelligence*

The second principle behind the concept of biocivilisations is social intelligence. The features of human civilisations that Niall Ferguson identified as "feeding, watering, sheltering and defending" apply to any social group, irrespective of whether that group is bacterial, protist, fungal, plant, or animal. Every single species that emerged in the history of life is a group of organisms that share a cognitive space (Uexküll van, 2010). Part and parcel of any cognitive space is the birth of social

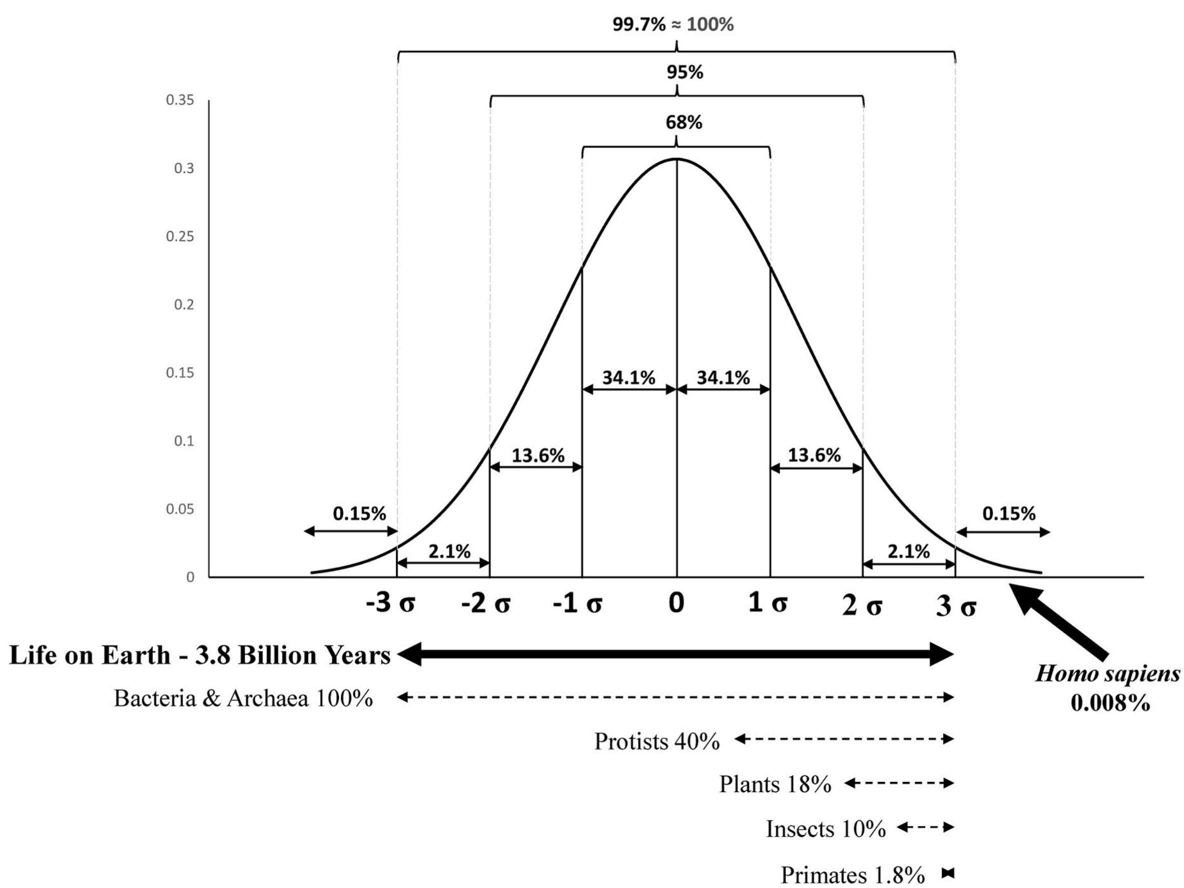

Fig. 2. Timelines of various organisms in the course of evolution expressed as percentages of the bacterial/archaeal timeline. Reproduced from Slijepcevic (2023) with permission.

intelligence (Slijepcevic, 2018) at the heart of which is communication between individual members, as recognised by the field of biosemiotics. Jasper Hoffmeyer (2015) described the totality of communicative, species-specific social interactions in the biosphere, known as the semiosphere, in the following way: “Nature in fact is not so much about ‘tooth and claw’ as it is about sensing, interpreting, coordinating, and social cooperation.”

Social intelligence can be traced to the capacities of cells to communicate with each other. Communication is part of their extensive cognitive repertoire that integrates the information space known as PIF (Pervasive Information Field) with (i) the senome, the sum of the cell’s sensory experiences guided by the bioactive capacity of the plasma membrane as the interface between the cellular self and the environment and the cytoskeletal elements responsible for the cellular internal structure (Miller 2016; Baluška and Miller, 2018; Reber et al., 2023; Baluška et al., 2023), and (ii) the N-space episenome, the sum of sensory experiences of cells within the multicellular conglomerates of plants and animals (Miller et al., 2020, 2023; Reber et al., 2023). In the social context, PIFs and senomes aggregate as N-space episenomes, acquiring a new dimension whereby the social interactions exceed species-specific cognitive spaces and extend to inter-species and cross-kingdom interactions as in holobionts, and also to the biosphere-wide interactions of all extant species known as the interactome (Slijepcevic, 2021). The interactome represents the system-level, or the biosphere-wide communicative space, integrating all cell types, from prokaryotic cells and derivative eukaryotic cells that emerged through endosymbiosis, to conglomerates of eukaryotic cells integrated into corporate bodies of plants and animals, which in turn interact with prokaryotic cells forming holobionts (Fig. 3). The interactome fits well the nested structure of the biosphere in the context of cognition, incorporating the heterarchical elements as depicted in Fig. 1 B. All biogenic forms merge into multi-species conglomerates of large ecosystems such as mature forests (Ulanowicz, 2002) that represent the largest sub-system parts of the biosphere (Fig. 3). The key systemic feature of the biosphere as the conglomerate of socially interacting species through the synergy of their cognitive spaces, is the constant flow or homeorhesis – the capacity of the system to maintain integrity by moving along a trajectory defined by constantly changing parameters (Fig. 3). While homeostasis represents the maintenance of the steady state of multicellular bodies, homeorrhesis represents the movement of a constantly changing biospheric system around moving setpoints including temperature, gas concentrations, pressure, etc. (Margulis, 1990). (The distinction between homeostasis and homeorhesis can be observed in Fig. 1 B – the movement from one level of cellular hierarchy to another, e.g. from 1 to 1^e, provided that levels differ structurally; e.g. prokaryotic vs. eukaryotic cells.) It is now well established that the biospheric system can regulate itself in a decentralised process integrating all its communicating parts (Rubin et al., 2021, Fig. 3). Thus, social intelligence is pervasive, and it is at the heart of the biosphere self-regulation. This is also recognised by researchers focusing on the concept of autopoiesis: Niklas Luhmann coined the term “social autopoiesis” to integrate communication processes with the autopoietic structure of the biosphere (cited in Capra, 2022).

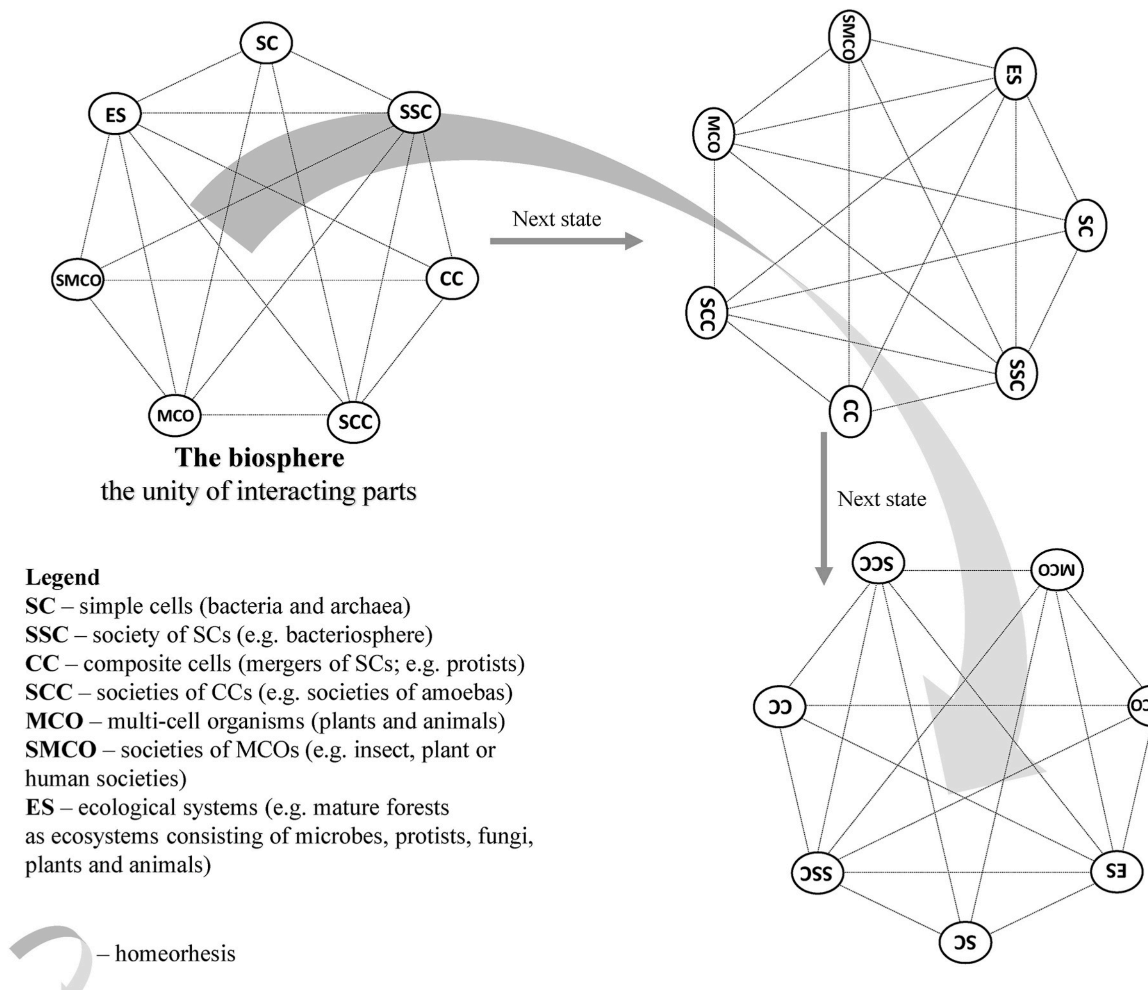

Fig. 3. The biosphere as the cell-based interactome. Modified from Slijepcevic (2023) with permission.

3.3. Evolutionary convergence

The third principle behind the concept of biocivilisations derives from a well-known process of evolutionary convergence, whereby biogenic forms and functions repeat in evolutionarily distant organisms (Conway-Morris 2003, 2006; Stern 2013; Powell and Mariscal, 2015). The process of evolutionary convergence represents a suitable basis for elaborating how macroevolutionary effects of social intelligence turn into biocivilisations – morphological ripples on the "body" of the biosphere repeating at different temporal and spatial levels of the biosphere structure and originating from the roots located in the molecular properties of cells as indivisible units of agency and cognition (Fig. 1 B). Importantly, the process of evolutionary convergence is a heterarchical rather than hierarchical process (Fig. 1 B).

These periodic morphological ripples are hallmarks of social intelligence – extensive, biosphere-wide social cooperation (Fig. 3) results in complex patterns that various species build in the course of evolution. I have identified a total of six hallmarks of social intelligence that occur in all kingdoms of life (see below in this section, and also section 4). By the principle that *Homo sapiens* is an outlier on the curve of life (Fig. 2), and the logical shift from the human-centred cognition to the biosphere-wide equivalents (Fig. 3), the human concept of civilisation, based on human social intelligence, dissolves into a biosphere-wide continuum of biocivilisations that integrate into the system level organisation of the biosphere. Let us connect social intelligence with evolutionary convergence.

According to Conway-Morris (2003, 2006), evolutionary convergence is the defining feature of the biosphere that may allow us, or even cognitively proficient extraterrestrials unfamiliar with the biosphere, to predict future macroevolutionary patterns based on past convergent events. Conway-Morris (2006) was explicit about the role of social intelligence in evolutionary convergence: "So too, in terms of social systems, think of the colossal convergence between elephants and sperm whales. Then there is eusociality, a system that has evolved repeatedly in insects and moreover in shrimps and even mammals, in the case of the naked mole rats. The mole rat is one of the very few examples in biology where a system was predicted before it was actually recognised. So, our planet may actually provide a very good guide to alien biospheres." Conway-Morris did not mention bacteria in the context of evolutionary convergence, but a recent study revealed bacterial engineering skills, during the process of biofilm construction, that resemble certain aspects of urbanisation (Paula et al., 2020), which is a form of evolutionary convergence found in social insect societies (Wilson, 2012) and human societies (Slijepcevic 2023).

Conway-Morris (2006) further argued that the evolutionary convergence is rooted in genetic, molecular, and cellular events. For example, the key enzyme in CO_2 metabolism, a metalloprotein known as carbonic anhydrase, emerged independently in evolution at least five times, while photosynthesis involving C4 evolved no less than 30 times. In the context of social intelligence, one may argue that cognition represents the most widespread form of evolutionary convergence. Every single life form that emerged from the first cells – bacteria and archaea – shares basic cognitive functions with them (Baluška et al., 2023; Reber et al., 2023). At the social level – irrespective of whether organisms are single-cell prokaryotes, single-cell eukaryotes, or multicellular conglomerates such as plants and animals – cognitive functions of cells translate into similar morphological macroevolutionary patterns recognised as hallmarks of social intelligence.

I have identified a total of six hallmarks of social intelligence: communication, engineering, science, medicine, art, and agriculture (Table 1). The terminology inevitably reflects the anthropocentric bias. However, to avoid anthropocentrism, each hallmark of social intelligence has a derivative name (e.g. "communication" becomes "semiosphere") (Table 1) to reflect the naturalist roots. These derivative names reflect a wider evolutionary perspective and will be explained in the next section.

Table 1
The list of hallmarks of social intelligence including non-anthropocentric synonyms.

Hallmarks of social intelligence	Non-anthropocentric terms
Communication	Semiosphere
Engineering	Autopoiesis
Science	Problem-solving
Medicine	Self-preservation
Art	Aesthetics of doing
Agriculture	Group feeding

In summary, the three principles behind the concept of biocivilisations open the avenue for exploring this concept in greater detail by focusing on the hallmarks of social intelligence repeating in all kingdoms of life.

4. Hallmarks of social intelligence

In this section, I shall focus on how hallmarks of social intelligence, as defining features of biocivilisations, occur periodically in all kingdoms of life. Thus, the concept of biocivilisations is a heterarchical rather than hierarchical phenomenon: biological forms and functions "travel" back and forth within the spatio-temporal body of the biospheric system. The only hallmark that will not be discussed in this paper is art. I intend to present art, in the context of biocivilisations, in a separate paper.

4.1. Communication

It has been argued that bacterial communication systems have analogues of information exchange and interpretation of meaning that exist in human languages (semantic and pragmatic). For example, Ben-Jacob et al. (2004) demonstrated how bacteria use genomic plasticity to conduct processes of social communication by relying on shared interpretation of chemical cues and exchange of chemical messages that typify bacterial linguistics. Similarly, communication in plants has been interpreted as a form of language whereby VOCs (volatile organic compounds) that plants use in their communication have been likened to "words", and a combination of VOCs to "sentences" in plant language (Holopainen and Blande, 2012). Thus, continuity of communication as the first hallmark of social intelligence is relatively easy to observe among different kingdoms of life. This is recognised by the discipline of biosemiotics which explores communication in nature as the basis for cognitive interpretation of meaning specific to each kingdom of life: zoosemiotics, phytosemiotics and protosemiotics (bacteria, archaea, protists and single-cell fungi) (Sebeok, 2001). For this reason, and as argued earlier, the synonym for the term communication is the semiosphere (Table 1) – the biosphere-wide communicative continuum as the basis for the meaning-making process of cognition (Fig. 3).

Table 2
Modes of communication in the living world.

Kingdom of Life	Mode of Communication		
	Physical	Chemical	Biological
Bacteria & Archaea	EI	QS, VOCs	HGT
Protists	HW	QS	GA
Fungi		VOCs	
Plants	Touch, Sound, Vision, El	VOCs, ST	GA, EV
Animals	Sound, Vision, Touch, Hearing, El	VOCs, H, P, SM	GA, EV

Abbreviations: EI – electrical impulses; QS – quorum sensing; VOC – volatile organic compounds; HGT – horizontal gene transfer; HW – hydrodynamic waves; GA – genome acquisition; H – hormones; P – pheromones; SM – signalling molecules; EV – extracellular vesicles. Empty boxes in the Fungi row indicate a lack of literature for a particular mode of communication.

The modes of communication in all kingdoms of life are presented in Table 2 and are classified into physical, chemical, and biological modes. The purpose of Table 2 is to provide simple guiding principles rather than to generate an exhaustive database of communication modes. These modes include (i) exchange of chemical messages (quorum sensing) (Bassler, 2002) and electrical impulses (Prindle et al.,) in bacteria, (ii) use and exchange of VOCs in protists and plants (Schulz-Bohm et al., 2017; Holopainen and Blande, 2012), (iii) use of signalling molecules in protists (Luporini et al., 2016) and in cells within multicellular bodies of plants and animals (Hancock, 2017), (iv) use of hormones, hormone-like molecules and pheromones in all kingdoms of life (Hancock, 2017), (v) use of physical signals such as hydrodynamic waves in protists (Mathijssen et al., 2019), (vi) use of sound signals in plants and animals (Andreas et al.,; Vallejo-Marin and Cooley, 2021), (vii) use of extracellular vesicles in cells of plants and animals.

(van Niel et al., 2018), (vii) HGT in bacteria and archaea (Goldenfeld and Woese, 2007) and genome acquisition in eukaryotes (Margulis and Sagan, 2003), (ix) senses of vision and hearing in plants and animals (de Mayo, 2015) and other still unidentified processes. The cross-kingdom communication, which is not included in Table 2, is also extensive (Fig. 3).

4.2. Engineering

In simplest terms, engineering in the context of the biosphere means building complex structures including (i) bacterial biofilms (Flemming and Wingender, 2010) and protist "houses" (Hansell, 2011), (ii) ant, termite and honeybee nests (Wilson, 2012; Slijepcevic, 2023), (iii) animal tools (Shumaker et al., 2011), (iv) engineering sites dominated by plants known as biomes (Woodward et al., 2004), (v) medical devices "invented" by bacteria to protect them from viruses (Bernheim and Sorek, 2020), (vi) ecological engineering sites managed by fungi, insects and snails (Wright and Jones, 2006), (vi) natural genetic engineering projects executed by bacteria (Shapiro, 2011) and many more.

To place engineering in the context of biocivilisations we need to tone down anthropocentrism and identify a synonym for engineering suitable for a wider evolutionary context. The synonym must be wide enough in its meaning to incorporate all elements of human engineering but universal enough to break the anthropocentric walls and incorporate all other species. I have selected the term technology as a starting point for the transition towards a synonym for engineering in the natural context – *autopoiesis* (Table 1).

The meaning of technology is so wide that different practitioners put their stamp on it making it difficult to share the concept with other practitioners. For example, technology has different meanings for information scientists, lawyers, and industries such as farming and milk industries. However, Richard Li-Hua (2013) explored these differences to identify what they have in common. This enabled him to produce a single platform universal enough to incorporate all forms of technology.

In Li-Hua's vision, technology has four components: technique, knowledge, organisation of the working process (production), and product (Fig. 4 A). The technique consists of instruments (tools and machines), materials, and the method for bringing instruments and materials together. Knowledge consists of applied science, skills, and intuition. The organisation of production means that technique and knowledge must be organised before they can produce results. The product integrates technique, knowledge, and organisation of production (Fig. 4 A).

However, Li-Hua's platform remains anthropocentric. Terms such as technique, science, and some other terms used in Fig. 4. A, are associated

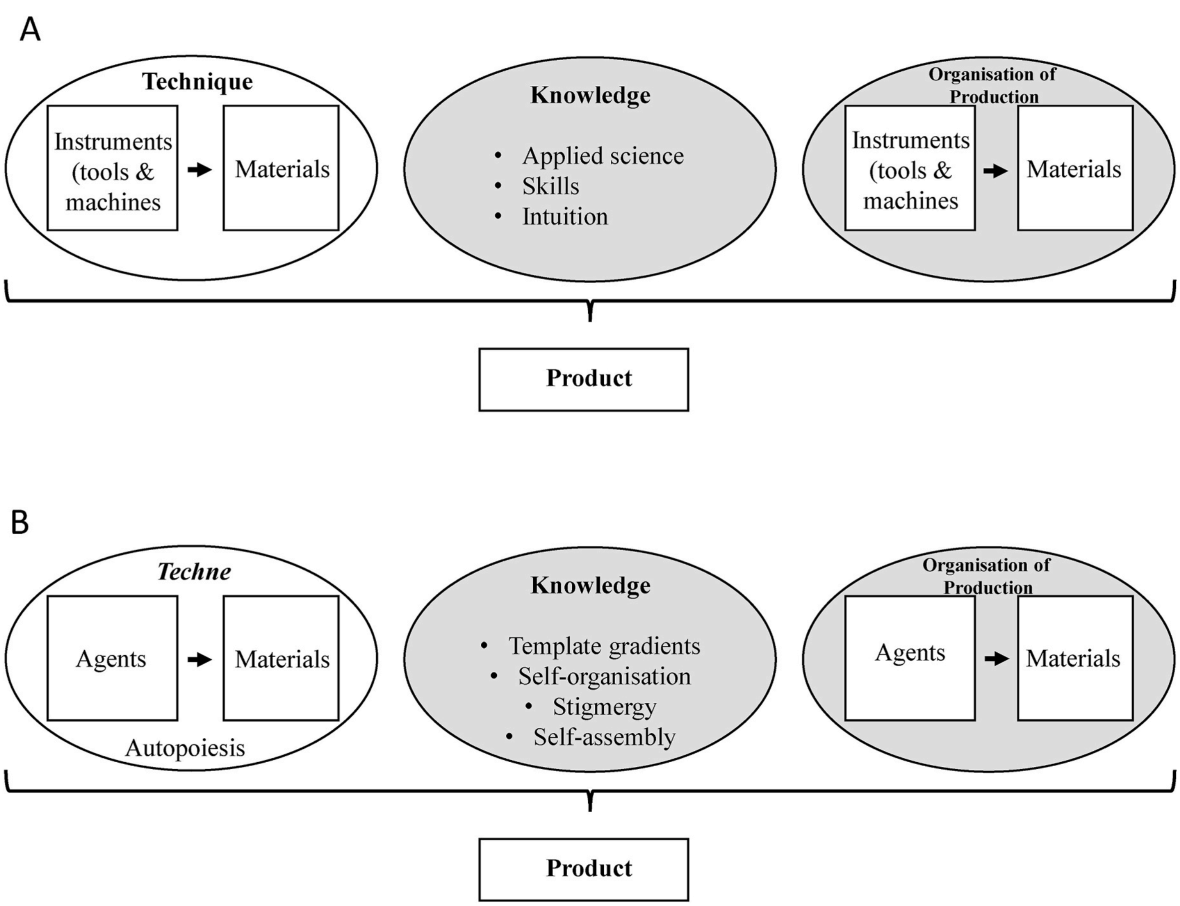

Fig. 4. A. Li-Hua's (2013) vision of technology. B. Incorporating techne and autopoiesis to obtain a naturalist vision of technology (see the text). Adapted from Slijepcevic (2023) with permission.

exclusively with the modern human culture. The anthropocentric bias can be reduced or even eliminated if we adopt an interpretation of technology used by ancient Greeks (Heidegger, 1977). Ancient Greeks used the word *techne* for technology, covering both technique and art. For ancient Greeks, artists and craftsmen were not the ultimate "makers" of art and craft products. Instead, artists and craftsmen were interpreted as conduits, together with tools and materials, in the technological process through which nature reveals itself to us. Philosophers called this process *poiesis* meaning bringing something into existence. In this interpretation nature or *physis* in Greek is the highest form of *poiesis* (Heidegger 1977). The term that faithfully captures the essence of engineering in the context of *techne* and *poiesis* is *autopoiesis*. This concept was invented by Maturana and Varela (1980) to describe how nature constantly reconstructs and reinvents itself because it consists of autopoietic units: organisms as self-producing, self-organising and self-maintaining agents.

When Li-Hua vision of technology (Fig. 4 A) is adapted to include *autopoiesis* (Fig. 4 B) we get a platform that can faithfully describe any form of engineering in the context of biocivilisations. The consequence of the new model is that instruments and tools (Fig. 4 A) are replaced by agents (Fig. 4 B) – the autopoietic units ranging from bacteria to mammals. Agents sense environmental stimuli and respond to them, thus acting as sensitive body instruments. It is important to stress that agents are autopoietic units fundamentally different from machines as demonstrated by Robert Rosen (1991).

Let us examine bacterial and social insect engineering skills used in the construction of biofilms, and insect nests, respectively in light of Fig. 4 B. The construction of bacterial biofilms has seven phases encompassing settlements such as villages and cities culminating in the bacterial megacity (Watnik and Kolter, 2000; Paula et al., 2020). Social insects build their nests in a long process that can take up to five years in the case of termites (Keller, 1998). Throughout the building process, bacteria sense multiple parameters in the environment ranging from temperature and humidity gradients to surface hardness (Flemming and Wingender, 2010). On the other hand, the bodies of social insects act as chemoreceptors, mechanoreceptors, thermoreceptors, and hygroreceptors (Theraulaz et al., 1998, 2003; Heylighen, 2016). Agents use suitable materials for building. Bacterial cells secrete carbohydrates, proteins, lipids, and even DNA and use them as building materials known as EPS (extracellular polymeric substances) (Watnik and Kolter, 2000; Flemming and Wingender, 2010). Social insects search for suitable materials in the environment, from soil to water. Knowledge in the case of social insects can be interpreted as a form of intuition. Ethologists identified four types of behaviour in social insects that allow them to construct complex nests: reliance on template gradients, self-organisation, stigmergy, and self-assembly (Theraulaz et al., 1998, 2003; Heylighen, 2016). In the case of bacteria, knowledge remains poorly understood, but it is likely to be rooted in the cognitive properties of bacterial cells which extend into forms of social intelligence. The organisation of the working process in social insects is guided by the division of labour through a caste system (Wilson, 2012), while in the case of bacteria this aspect has not been extensively investigated. However, some researchers suggested that a division of labour may exist even in bacterial colonies (Ben-Jacob, 2009; Slijepcevic, 2021). The product is the construction of a shelter for both groups of agents, bacteria and insects, a process dubbed "urbanization" in the case of bacteria (Paula et al., 2020).

It is important to stress that the cases of bacterial and insect engineering do not require central planning or production of engineering blueprints like in the case of human engineering. Non-human agents follow simple biosemiotic rules that allow them to form decentralised societies capable of changing environments by reading and interpreting environmental cues. One may say that the blueprint for bacterial and insect "cities" is hidden in the environment: in the structural coupling between agents as cognitive units and environmental heterogeneities acting as biosemiotic signals that attract agents and prompt them to execute meaning-making episodes constrained by the rules of their cognitive spaces.

4.3. Science

A philosopher of science, Karl Popper (1979, 1999), a proponent of evolutionary epistemology, interpreted science as a problem-solving exercise through error elimination that has naturalist roots in non-human organisms. Popper famously remarked that there is no difference between Einstein and an amoeba in their quests for knowledge (Popper, 1979, p 261). Popper's arguments can be used to obtain a suitable synonym for science as a hallmark of social intelligence in non-human organisms – problem-solving through error elimination (Table 1).

Here is how Popper (1979) formalised problem-solving. If the problem is denoted as P, its solution, or the tentative solution, as TS, and the error elimination as EE, this natural process may be described as follows:

$$P \rightarrow TS \rightarrow EE \rightarrow P$$

However, a solution to a problem always creates a new problem. For example, if bacteria solve the problem of survival in the presence of an antibiotic, through antibiotic resistance, the newly acquired chemical pathway may force bacteria to change certain metabolic habits leading to a new problem. This new problem is always different from the first one. Therefore, a more accurate formula is:

$$P_1 \rightarrow TS \rightarrow EE \rightarrow P_2$$

Even this formula is incomplete because it ignores the multiplicity of solutions and the multiplicity of trials. For example, organisms as cognitive agents are always confronted with environmental heterogeneities leading to multiple solutions and multiple trials, a process of endless problem-solving. Popper's (1979) final formula is:

$$P_1 \rightarrow (TS_1, TS_2 \ldots TS_n) \rightarrow EE \rightarrow P_2$$

Popper interpreted problem-solving in the context of MS. In other words, the multiplicity of tentative solutions, or TS, for any existential problem is the variety of mutations. However, given that the basic principles of MS are refuted (Shapiro, 2011; Noble 2013), Popper's framework works equally well, if not better in the context of CB – social intelligence, including problem-solving, is rooted in the cognitive capacities of cells, rather than being driven by random mutations.

Examples of problem-solving across various kingdoms of life are numerous. To demonstrate some of these, we can use one of the principles behind evolutionary epistemology –all forms of evolutionary knowledge are interchangeable between kingdoms of life (Campbell, 1974), another example of the heterarchical nature of biocivilisations. This means that a solution to a problem invented by one life form may be "copied" by another, a possibility in line with the evolutionary convergence (see section 3). We know from the scientific discipline of biomimetics that humans use solutions invented by other organisms to solve problems encountered in various human industries (Vincent et al., 2006). Three such examples are briefly described below.

Bacteria possess six types of immune systems, invented as solutions to the problem of viral infections (Bernheim and Sorek, 2020). One of these immune systems is CRISPR (clustered regularly interspaced short palindromic repeats) (Lander, 2015). Billions of years after the original bacterial "invention" of CRISPR, scientists discovered this process and copied its basic principles to invent a method for genome editing leading to a Nobel prize in chemistry (Ledford and Callaway, 2020).

Faced with the problem of internet traffic congestion, a group of engineers teamed up with a honeybee expert, to copy a solution honeybees invented to solve the problem of nectar collection from a flower field. This solution was applied to the problem of internet traffic, leading to the invention known as the honeybee algorithm (Nakrani and Tovey, 2007). The American Association for the Advancement of Science (AAAS) awarded the Golden Goose award to the team behind the invention in 2016, while the invention itself made savings of $10 billion to internet companies (Professor Thomas Seeley, personal communication).

Finally, cognitive capacities of an ameboid species, *Physarum polycephalum*, have been demonstrated in various studies, including finding the shortest route to food in a maze (Nakagaki et al., 2000), selecting the most nutritious meal from a group of dozens meals on offer (Dussutour et al., 2010), and reconstructing the railway network around Tokyo in an experiment guided by distributing food sources in a specific spatial pattern (Tero et al., 2010). A detailed analysis of the cognitive skills of this ameboid species enabled scientists to produce a mathematical model for constructing adaptive networks relevant to human engineering (Tero et al., 2010).

4.4. Medicine

The cognitive repertoire of cells includes self-preservation. For example, bacteria developed six types of immunity to counter viral infections (Bernheim and Sorek, 2020). In addition, virtually all cells activate stress responses when exposed to external insults including heat shock response, oxidative stress response, DNA damage response, and the unfolded protein response (Slijepcevic 2007; Fulda et al., 2010). Given that the roots of all social intelligence hallmarks, including medicine, are in cognitive capacities of cells, one may argue that medicine, as practiced by humans, is a special case of self-preservation (Table 1) that has parallels in bacterial (Bernheim and Sorek, 2020), plant (Nishad et al., 2020) and animal (McFall-Ngai, 2007) immunities, but its direct roots are in the animal self-medication.

Self-medication is practiced by social insects. They live in tightly packed nests and are under constant threat from microbial pathogens and epidemics. To counter these dangers some ant, bee, and wasp species collect pieces of solidified resin and place them in their nests. Since resin contains chemicals with anti-bacterial and anti-fungal properties, this behaviour is reminiscent of prophylactic medicine (Castella et al., 2008). Wood ants also combine antimicrobial liquids secreted by their glands, including formic and succinic acids, with resin pieces to produce more potent killing of a fungal pathogen, *Metarhizium brunneum*, relative to the treatment with the resin alone (Brütsch et al., 2017). Interestingly, warrior ants, from the species *Megaponera analis*, treat injured fellow ants with antimicrobial liquids in an organised fashion (Frank et al., 2017, 2018).

Self-medication was observed in numerous other animal species. It represents the practice of using plants and non-nutritional substances to treat diseases. Four criteria are used to identify self-medication: (i) plants used for self-medication must not be part of the animal's regular diet, (ii) self-medicating plants must lack nutritional value, (iii) the use of self-medicating plants must coincide with the period when the disease frequency is at the highest level and (iv) unaffected animals must not use self-medicating plants (Shurkin, 2014). Using these criteria self-medication has been observed in numerous species from different phyla: bears, deer, elks, porcupines, jaguars, lizards, fruit flies, butterflies, elephants, woolly spider monkeys, lemurs, baboons, great apes, and domesticated animals such as goats and llamas (Shurkin, 2014). The practice of animal self-medication covers a period of 400 million years of evolution.

Studies in ethnomedicine and ethnoveterinary medicine revealed that the practice of self-medication emerged in our hominin relatives and *Homo sapiens* through (i) sharing information between different hominin groups and (ii) observing and copying actions of other animals. Archaeological records show that different groups of Paleolithic hominins used the same plants for self-medication (Huffman, 2022). Also, medicinal plants and fungi that are still in use by modern humans, including chamomile, yarrow, and the fungus *Penicillium rubens* were used by Neanderthals (Huffman, 2022). A representative example of observing other animals is the case recorded early in the 20th century (Huffman, 2001). A medicine man, Babu Kalunde of Tanzania, observed how a porcupine with blood in stool used the root of a poisonous plant known by locals as *mulengelele* (*Aeschynomene cristata*) to cure the ailment. Babu Kalunde experimented on himself to determine a safe dose of the plant and treated locals when they suffered from dysentery-like diseases. The root of *mulengele* likely contains natural antibiotic substances. Kalunde's grandon used *mulengelele* to treat sexually transmitted diseases such as syphilis and gonorrhea.

It seems reasonable to argue that modern medicine emerged from the traditional knowledge of hominins, Neanderthals, and indigenous *Homo sapiens* societies over several thousand years. Successful cases of traditional medicinal knowledge survived and merged with ancient Egyptian, Chinese, and Indian medicinal practices. These practices continued with the Graeco-Roman culture, as we know from Aristotle's *History of Animals*, modernised by the Greek philosophical thinking and further enriched with experiences of Islamic medicine and European medieval medicine, culminating with the introduction of science into medicine during the Enlightenment period, resulting in the birth of modern science-based medicine (Alvaró et al., 2019).

4.5. Agriculture

Scientists who investigate agriculture in an evolutionary context identified close links between insect fungiculture and human farming. It is well documented that agriculture in insects emerged several times over the last 50 million years, in ants, termites, and ambrosia beetles (Mueler et al., 2005). In all cases, insects propagate monoclonal cultures across many generations. Similarly to human farmers, insect farmers developed effective strategies to manage crop diseases. Given that the purpose of farming in insects and humans is to feed large social groups that share habitats, an appropriate synonym for agriculture in the evolutionary context is group feeding (Table 1).

However, farming in insects and humans goes beyond fungal and plant cultivar propagations. Human farming includes animal husbandry for the production of meat, dairy, eggs, wool, and other products and consists of traditional farming of cows, sheep, goats, pigs, and poultry, as well as some non-traditional practices such as farming insects for food (Hanboonsong et al., 2013), sericulture, aquaculture, beekeeping and farming some rodent species for clothing purposes.

Animal husbandry occurs outside the human culture. Ants and aphids developed a symbiotic relationship whereby ants act as herders of these sup-sucking soft-bodied insects, also known as "ant cows" (Saha et al., 2018). Ants not only "milk" aphids to extract nutritious honeydew, but also occasionally eat these insects to supplement the diet. This is analogous to the simultaneous human usage of meat and milk from cows, sheep, or goats.

Farming practices occur outside the animal kingdom. A social amoeba, *Dyctiostelium discoideum*, and a bacterial species from the genus *Burkholderia* established a symbiotic relationship with elements of farming practices whereby amoebas act as bacterial farmers depending on nutritional conditions (di Salvo et al.,). Furthermore, the soil fungus *Morchella crassipes*, farms bacterial species *Pseudomonas putida* (Pion et al., 2013) by habitually planting bacteria, feeding them with fungal exudates, and harvesting them for food.

In summary, hallmarks of social intelligence (Table 1) are shared by all kingdoms of life because first life forms – bacteria and archaea – are basic and indivisible units of biological agency from which all other agents emerged.

5. Discussion

When the arguments presented in sections 2-4 are reduced to the simplest explanatory constituents, it turns out that biocivilisations are driven by the cognitive capacities of first cells (Figs. 1 and 3). To give this position a formal scientific grounding, including testing and predictions, I have linked biocivilisations with the concept of evolutionary convergence whereby similar biogenic forms and functions emerge independently in different kingdoms of life (Conway-Morris, 2003, 2006) (see also Fig. 1). This is consistent with the notion of heterarchy, introduced by Warren McCulloch (1945), and extended to biological systems in the context of cognition, to describe the network of interacting minds (all organisms) leading to bottom-up and top-down causal links within the biospheric system (Bruni and Giorgi, 2015) (Fig. 1 B).

The consequence of this new position is the revival and revision of the 19th-century cell theory, in line with CBC (Reber et al., 2023) and CBE (Miller, 2023) theories proposed earlier: cells are not only basic units of life but also basic units of cognition, sentience, and consciousness. The cell cognitive competence (Figs. 1 and 3) extends to the structural and functional organisation of the biosphere through hallmarks of social intelligence (Table 1). These hallmarks are repeating morphological patterns within the body of the biosphere (section 4), or biocivilisations (Slijepcevic 2023). This is a radical shift in the science of life – akin to a Copernican turn – from the mechanistic gene-centric view that excludes cells from the chain of causation to the Kantian CB position (section 2) according to which the chain of causation remains within organisms, starting with first cells, archaea and bacteria, from which all other organismal forms emerged (Fig. 3).

The key motivation for the turn is the fundamental error of MS which gives genes the role of powerful and universal biological agents. This position is untenable. The basic and indivisible unit of agency in the living world is the simplest cells, archaea and bacteria. All other agents are derived from bacteria and archaea either through the process of endosymbiosis or through the process of multi-cellularity emergence. Biogenic forms below agents are viruses and viroids (Tsagris et al., 2008), plasmids (Couturier et al., 1988), retrotransposons and transposons (Goodier, 2016), prions (Prusiner, 1998), and extra-cellular vesicles (Veziroglu and Mias, 2020). Agents can actively incorporate these sub-agential biogenic forms into their bodies, or shape them according to their needs, a process that has been dubbed natural genetic engineering in the context of genome reshaping (Shapiro, 2011). Also, agents can counter the uncontrolled integration of sub-agential biogenic forms into their bodies as exemplified by the development of six forms of immunity in bacteria to prevent viral infections (Bernheim and Sorek, 2020).

The new position has a solid potential for testing and further development into a formal theory. Hallmarks of social intelligence are grounded in the cell theory. The concept of heterarchy, as discussed by Bruni and Giorgi (2015), opens a route towards a deeper integration of the cell theory with CB. In addition, one can go beyond social intelligence. For example, Lyon (2015) proposed that individual agents such as bacteria possess "cognitive toolkits" consisting of various functional capacities from sensing and perception to valence, decision making, and others. This opens a possibility of focusing on cognitive functions specific to individual agents (Slijepcevic 2018). The separation of the individual and social cognitive features could provide the basis for addressing how cognitive functions evolve from simple to complex (Lyon et al., 2021). Or for addressing differences between, for example, CBC which views cognition, sentience, and consciousness as cellular properties (Reber et al., 2023), and the conventional view which recognises consciousness only in organisms with brains (Trewavas, 2017). It is clear that brains exist only in the animal kingdom. Given that animals are evolutionary late comers (last 600 million years) and that they constitute ~1% of the biosphere by biomass (Bar-On et al., 2018), mainstream science treats consciousness as a rare biological function, a position that ultimately promotes exclusivity and superiority of animals in general, and humans in particular, over other life forms. However, the existence of brains may simply be an anatomical-physiological necessity. Mobile multicellular agents such as animals, require a central information-processing organ to constantly monitor the ever-changing environment (Musall et al., 2019). Plants, as sessile agents, do not require this central processing organ (Trewavas, 2021).

In conclusion, biocivilisations are driven by cells as basic units of the biological agency. The starting point in the emergence of biocivilisations is the first life forms, archaea, and bacteria. Human civilisation is the latest addition to the evolutionary continuum of biocivilisations.

CRediT authorship contribution statement

Predrag Slijepcevic: Conceptualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

I do not have competing interests to declare.

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