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Opinion

Information in the Biosphere: Biological and Digital Worlds

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Evolution has transformed life through key innovations in information storage and replication, including RNA, DNA, multicellularity, and culture and language. We argue that the carbon-based biosphere has generated a cognitive system (humans) capable of creating technology that will result in a comparable evolutionary transition. Digital information has reached a similar magnitude to information in the biosphere. It increases exponentially, exhibits high-fidelity replication, evolves through differential fitness, is expressed through artificial intelligence (AI), and has facility for virtually limitless recombination. Like previous evolutionary transitions, the potential symbiosis between biological and digital information will reach a critical point where these codes could compete via natural selection. Alternatively, this fusion could create a higher-level superorganism employing a low-conflict division of labor in performing informational tasks.

Trends

Digital information is accumulating at an exponential rate and could exceed the quantity of DNA-based information.

There are biological and social implications arising from our growing fusion with the digital world.

The parallels between evolution in the biological and digital worlds need to be explored.

Information, Replicators, and Evolutionary Transitions

The history of life on Earth is marked by numerous major transitions in replicators, each corresponding to changes to the ways in which information can be stored and transmitted [1]. Examples include the transition of RNA replicators to the storage of biological information in DNA, single cells transitioning to multicellularity, and multicellular organisms replicating information in the form of learned behavior [2] leading to social superorganisms united by behavior, culture, or language [3,4] (Table 1). Each transition is dependent on the existing activity of the previous replicators (Figure 1).

In contemporary human society, information, cultural expression, and language are now being replicated at multiple points around the globe via interconnected digital systems. These digital replicators are bound by similar rules and exhibit parallels with previous biological innovations in information processing. The accumulation of digital information is occurring at an unprecedented speed. After RNA genomes were replaced with DNA, it then took a billion years for eukaryotes to appear, and roughly another 2 billion for multicellular organisms with a nervous system (Figure 1). It then took another 500 million years to develop neural systems capable of forming languages. From there, it took only 100 000 years to develop written language and a further 4500 years before the invention of printing presses capable of rapid replication of this written information. The digitalization of the entire stockpile of technologically mediated information has taken less than 30 years. Less than 1% of information was in digital format in the mid-1980s, growing to more than 99% today (extrapolated from [5]).

In terms of brute force power, we have reached a stage where artificial information processing has matched the rates at which living things process information. The world's computers can perform orders of magnitude times more instructions per second than a human brain has nerve impulses and digital storage capacities vastly exceed the storage potential in the DNA of the human adult [5]. If these trends continue (Figure 2), the amount of digital information will eclipse that of nucleotides in the carbon-based biosphere within a century. Consequently, human

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Table 1. Evolutionary Characteristics of Some Informational Transitions During the History Of Life[a]

	Pre-3.8 bya (RNA)	3.8 bya to Present (DNA)	0.1 mya to Present (Culture)	Present to Future (Biological–Digital)
Replicating Unit What is the basic unit of replication?	RNA (ribonucleotides)	Genotype (deoxyribonucleotides)	Natural language (phonemes, graphemes)	Binary code (bit)
Fidelity of Replication How many errors per replication event?[b]	1×10^{-4} to 1×10^{-6}	1×10^{-8} to 1×10^{-10}	Low fidelity – oral Medium – scribe copy High – printing	$\sim 1 \times 10^{-6}$ to 1×10^{-17} (scalable bit error ratio)
Maximum Complexity How much information?[b]	1.7×10^{3} to 3×10^{4} bp (RNA viruses)	1×10^{6} to 1×10^{11} bp (cellular life forms)	1 to 1×10^{8} words (sentence to encyclopedia)	>> 8×10^{24} bits (1 yottabyte)
Expression How is the information expressed?	Ribozyme, protocell	Organismal phenotype	Human psyche (individual and collective)	Natural intelligence and AI (individual and collective)
Emergent Properties What evolutionary processes arise as emergent properties?	Metabolic pathways Cell membrane . . .DNA→	Multicellularity Neural complexity . . .language→	Cultural differentiation Science and technology . . .technological sphere→	Unknown

[a]Values are indicative not definitive and the list of transitions is not exhaustive [43].
[b]Representative data from [23,24,34,91].

activity has generated information storage and replication systems that are on track to contain more information than the combined information content of the cells and genes in the biosphere. What are the potential consequences for living things?

'Major transitions in the way information is transmitted very often arise when lower-level units coalesce into cohesive higher-level ones' ([6], see p. 184). This phenomenon applies to various evolutionary transitions, including, for instance, the eukaryotic cell, the rise of neural systems, and social insects, to name a few. Here we would argue that the coalescence of biological and digital information has a similar potential for the innovative transformation of life.

To explore this suggestion, we consider five aspects of more traditional replicators as specifically applied to digital information. First, storage of digital information has both similarities and differences to information stored as DNA. Second, digital code can be replicated differentially, thus increasing in abundance according to variations in relative fitness. Third, for this information to be acted upon it must be expressed to generate the digital equivalent of a phenotype. Fourth, digital information can be subject to selection but Lamarckian mechanisms might dominate neo-Darwinian mechanisms of natural selection. Finally, in biological information systems variation and novelty are generated by mutation, recombination, and differential expression and there are similarities and contrasts when these processes are executed using digital information.

The Digital Organism?

New biological systems often arise via combinations of simpler systems. This phenomenon spans multiple scales to include genes, cells, and individuals. Technological progress also arises by novel combinations of existing components, again on many different levels [7,8]. Heredity is paralleled by the combinatorial evolution of existing elements from simpler to more complex,

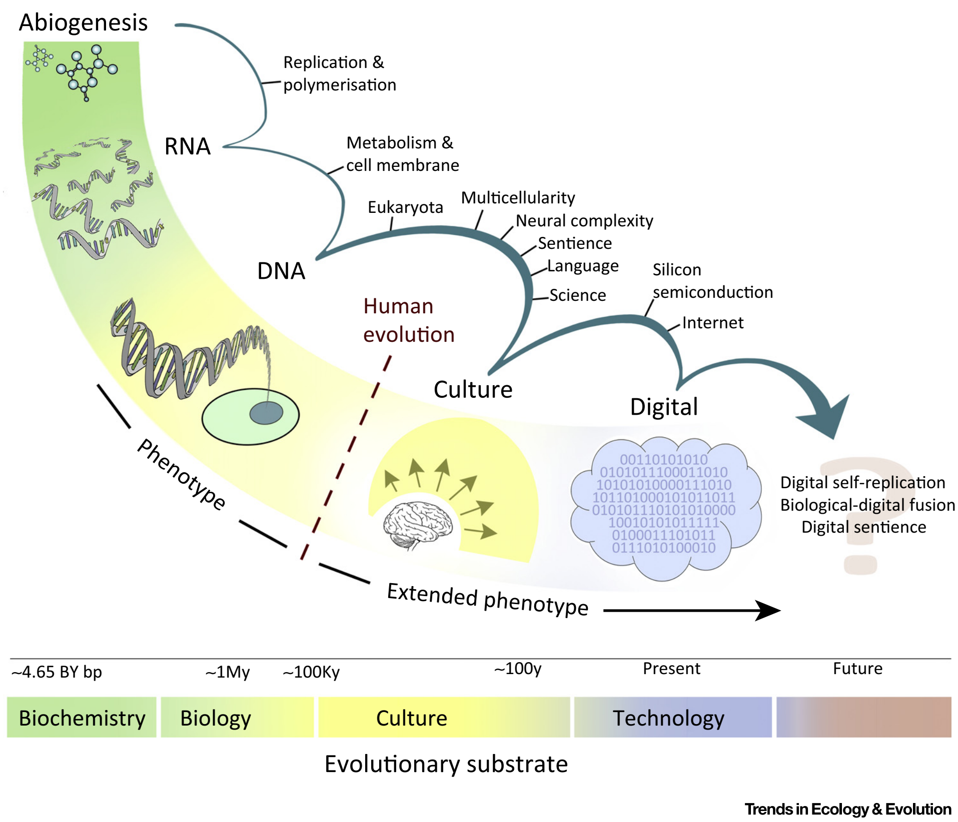

Figure 1. Schematic Timeline of Information and Replicators in the Biosphere.

while engineering and market mechanisms, expressed as utility and demand, parallel selection's filter [9]. The collective body of technology can be viewed as self-organizing (adaptive), energy transforming (produces, consumes, and exchanges energy with the environment), and autopoietic (self-producing new technology from its own parts), while increasing its fitness through replacement and differential growth of its constituent parts. So, in some senses, technology evolves, and leading scholars of technology consider that the collective of technology 'is indeed a living organism' ([9], see p. 189).

Traditional technology, from stone tools to steam engines and beyond, requires human agency. However, AI and robotics have challenged this restriction [10,11]. Machine learning has emerged as the method of choice for developing practical applications in AI. It can be more efficient to train systems through exposure, in line with biological learning, than using manual programming [12]. Autonomous vehicles on Mars, credit card fraud detection systems, and AI-controlled metro systems are powered by biologically inspired solutions using genetic algorithms [13], artificial neural networks [14], or 'deep learning' [15]. Deep learning comprises dynamic multilayer networks that employ billions of parameters to make sense of the world [16]. The outcome of learning from unlabelled audiovisual data [17] is strikingly similar to outcomes of neural networks employed by biological agents and contributes to our understanding of neurons [18]. Artificial agents bestowed with only rudimentary sensory recognition of pixels and a reward signal to increase a score can learn to outperform human experts in a matter of hours [19]. Newer generations of AI balance the inherent trade-off between data space and computational time, and in line with biological decision making [20]. The goal is not to be perfect but to be fit enough for a noisy environment. These developments have led to a 'unifying framework for the study of intelligence in minds, brains, and machines' ([21], see p. 278).

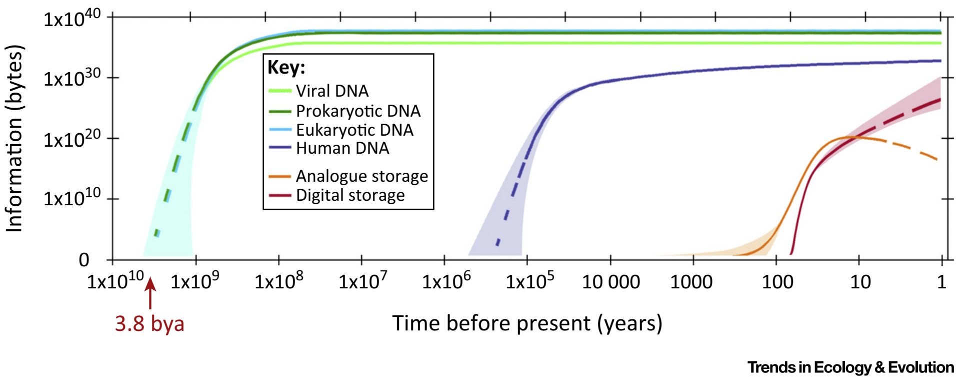

Figure 2. Schematic Illustration of the Increasing Quantity of Information in the Biosphere Over Time [5,24].

Using these criteria, digital technology can be considered on some levels as an organism in its own right. It is true that digital systems cannot replicate autonomously without access to energy and instructions to reproduce. However, this is not dissimilar to an animal or a plant deprived of energy or with a damaged reproduction program. It is now possible to bestow an artificial system with the will to survive, reproduce, and strive for increasing fitness.

Digital Storage

During the past three decades, the quantity of digital information stored has doubled about every 2.5 years, reaching about 5 zettabytes in 2014 (5×10^{21} bytes) (extrapolated from [5]). In biological terms, there are 7.2 billion humans on the planet, each having a genome of 6.2 billion nucleotides. Since one byte can encode four nucleotide pairs, the individual genomes of every human on the planet could be encoded by approximately 1×10^{19} bytes. The digital realm stored 500 times more information than this in 2014. Initiatives in brain mapping, space exploration, and national security all have plans for yottabyte storage facilities (10^{24} bytes) [22,23], demonstrating significantly expanding storage even in the short term (Figure 3).

The total amount of DNA contained in all of the cells on Earth is estimated to be about 5.3×10^{37} base pairs [24], equivalent to 1.325×10^{37} bytes of information. If growth in digital storage continues at its current rate of 30–38% compound annual growth per year [5], it will rival the total information content contained in all of the DNA in all of the cells on Earth in about 110 years. This would represent a doubling of the amount of information stored in the biosphere across a total time period of just 150 years (Figure 2).

Information technology has vastly exceeded the cognitive capacity of any single human being (*sensu* [25,26]) and has done so a decade earlier than predicted [27]. In terms of capacity, there are two measures of importance: the number of operations a system can perform and the amount of information that can be stored. The number of synaptic operations per second in a human brain has been estimated to lie between 1×10^{15} and 1×10^{17} [5,28]. While this number is impressive, even in 2007 humanity's general-purpose computers were capable of performing well over 1×10^{18} instructions per second [5]. Estimates suggest that the storage capacity of an individual human brain is about 10^{12} bytes [28,29]. On a *per capita* basis, this is matched by current digital storage (5×10^{21} bytes per 7.2×10^{9} people).

Digital Replication

Information can be viewed as a replicator, with similar properties to biological replicators [30]. This can be seen in the strong parallels between language and genes [31] and especially if words

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Figure 3. Information Available for Recombination in the Digital World (Potentially 1×10^{24} bytes, Large Globe) Compared with That Encoded by All of the Individual Human Genomes on the Planet (1×10^{19} bytes, Small Globe). Such comparisons illustrate the additional information that human activities have generated in the biosphere.

are thought of as autonomous informational structures [32]. Use of the terms 'transcription' and 'translation' to describe 'expression' of biological information illustrates how deeply these parallels run. Both genes and language have exhibited increasing fidelity of replication through time. In both cases, replication was initially not stringent: RNA genomes exhibit a high frequency of replication errors, as do spoken languages, whose component words and phonemes can exhibit rapid drift [33]. The invention of alphabets, written language, and printing parallels the improved storage of biological information in DNA, leading to orders of magnitude greater fidelity of replication (Table 1).

Fidelity of replication depends on the physical properties of the involved channel (its physical 'noise'), but given a certain channel capacity the error rate can be made arbitrarily small. This applies to all replication of information, as proven by the 'noisy-channel coding theorem', one of the foundational theorems of the digital age [34]. The fidelity of replication and storage of digital information can be orders of magnitude higher than that of DNA and, in principle, digital information can replicate in perpetuity with little or no degradation of information during copying at multiple locations.

Digital storage of biological information further improves the possibilities for fidelity of replication, since digital replication is essentially error free. Technical advances in DNA sequencing and synthesis mean that information originally encoded as DNA sequences can now be stored digitally for extended periods, with the potential for artificial re-synthesis of organisms at a later date [35]. This has already been achieved for bacteria [36] and syntheses of eukaryotic genomes are under way [37]. Re-synthesis of multicellular organisms will require greater understanding of developmental programming and epigenetics, but in principle these technological hurdles are not insurmountable. The replication of many thousands of digital genome sequences representing diverse species now occurs with virtually perfect fidelity at multiple nodes across the Internet. Continued accumulation of polished genome sequences will eventually result in a library of all of the information required to reconstruct a significant proportion of current biodiversity [38]. Storing this information indefinitely on solid media could be done without significant energy cost.

Digital Expression

Humans and digital technology share the same universal language, provided by the syntactic basis of information theory, and a universal grammar [39–41]. Both natural and computer languages come in many versions, such as Chinese and Belfast English or C++ and Python, but all are readily translatable and allow communication within and between biological and digital platforms.

Language, cultural assets, traditions, institutions, rules, and laws 'are the cohesiveness-maintaining mechanisms that integrate the "cultural individual"' ([42], see p. 308) and are seen as the main characteristics of the evolutionary transition that led to the superorganism we call human society [1,3,43]. All are currently being digitized and for the first time explicitly put into visible code. This exemplifies one of the characteristics of evolutionary transitions, that 'the new higher level becomes strongly cemented' ([6], see p. 187), in this case through digital reinforcement.

Digital code is also being expressed directly through the filter of intelligent algorithms. These activities include selection of the information that web users are exposed to [44], setting prices for resources [45], organizing workers to fulfill their labor duties [46], classifying human personality [47], and providing fully automated cognitive behavioral therapy [48].

Physical activity monitors can now automatically upload user data [49] and medical devices such as pacemakers can be wirelessly controlled via the Internet [50]. Brain–computer interfaces [51] and digitally mediated brain-to-brain interfaces [52] interact with neural activity as *ad hoc* or permanent brain extensions [53]. The outcomes are a potentially new mix of social behaviors based on traits resulting from expressions of both biological and digital code. For now, the social implications of this mix are not well understood [54,55].

Digital Selection

Digital selection, like that of biology, occurs through differential reproduction. However, in contrast to biological selection, the process is more Lamarckian than neo-Darwinian. In digital space, the analogies of natural selection and reproductive success are both mediated by expression, which changes the abundance of digital code. For instance, there have been over 750 million edits to Wikipedia pages (http://en.wikipedia.org/wiki/Special:Statistics), most of them directed rather than random. Some of the 500 million tweets sent per day will be re-tweeted and increase in abundance while many will languish as a single copy, never to achieve replication. Those from the USA become a digital equivalent to the fossil record by incorporation into the Library of Congress collection (http://www.Internetlivestats.com). Over 5 billion YouTube videos are viewed every day and emails are currently running at 150 billion per day (http://www.Internetlivestats.com). Each time a video or email file is downloaded, it is replicated and that package of information increases in abundance. The ease with which this occurs is because digital information exhibits almost infinite economies of scale, with almost zero cost of reproduction [56]. In some cases, the process of competitive selection is automated in its majority, as for example when computer viruses compete with antivirus software over vast networks, involving billions of digital hosts.

Consequently, the dynamics of selection in the digital world are different. Digital replicators do not compete for resources in quite the same way that living organisms do. They simply compete for reproduction. In this sense, modifications that improve the likelihood of reproduction are favored. At the same time, the rise and fall of relative fitness can be subject to highly unstable cycles. Digital code can explode virally within hours, spreading to billions of hosts, and then be forgotten days later.

There are potential limitations on digital replication, which is ultimately dependent on a supply of electrical energy. In theory, neither the recording nor the processing (expression, replication, or modification) of digital information requires energy, only its deletion. This is known as Landauer's principle in physics [57] and is at the heart of the intimate connection between information and energy [58]. We are far from Landauer's limit because we currently have enough energy sources to ignore the issue, and today's computers can afford to produce energetically wasteful heat. However, data centers have increased their share of global electricity use from 1% to almost 3% during the past decade [59] and Internet traffic is responsible for approximately 2% of global anthropogenic CO_2 emissions (http://www.Internetlivestats.com/), prompting serious reexamination of Landauer's principle [60–62]. Consequently, an augmented energy supply or a major technological innovation will be needed to sustain the continuing expansion of digital information. That said, information stored on a disk or USB stick is still more sustainable and energy efficient in preventing informational decay than is cellular DNA, which requires larger inputs of energy for maintenance.

Digital Variation

Fidelity of replication for digital information can be scaled up or down depending on circumstance, within Shannon's bound, typically being 15–17 significant decimal digits for a commercial laptop. Error rates are therefore multiple orders of magnitude lower than the mutation rate of even the most stringently proofread DNA molecule (Table 1). This means that digital equivalents of point mutation are extraordinarily rare per replication. However, the speed of reproduction for digital information is orders of magnitude faster than that of cellular life forms, where the shortest known doubling time is approximately 10 min (for a 5 million base pair genome) [63]. The speed of digital generation times may even out the realized ‘point mutations’ per unit time for the digital and biological worlds.

The variety generated by recombination of digital information can vastly outstrip that of DNA recombination. The largest known animal and plant genomes contain 1.29 and 2.58×10^{11} nucleotide base pairs respectively [64,65], equivalent to 30 gigabytes of information. A standard smartphone in 2015 has twice this capacity in storage and the total information content of the digital world will soon be 10^{13} times larger. In principle, all of this digital information is available for recombination, fusion, or coexpression (Figure 3).

Efforts are currently under way to convert the mainly unstructured data on global digital networks to machine-readable formats that are interpretable and recombinable by digital algorithms. The push for tagging data will help meta-analyses [66] as will the semantic web [67]. Standards such as the Resource Description Framework create a layer of meta-information between binary digits and human-readable data, thus providing semantic meaning to machines.

Machine-readable data can then be used by machines to search for new combinations. The outcomes of such recombination are already apparent in diverse fields, from social media to science. AI algorithms can compose music in the style of Mozart [68] and aim to compose global hit songs [69]. In general, data-mining activity driven by machine learning and other meta-analyses are directed forms of recombination. Newly found correlations provide information used for product recommendations at online retailers and news feeds on social media [55]. Meta-analyses also generate new concepts, syntheses, and tools in scientific fields as diverse as ecology [70], neuroscience [71,72], human genomics [73], and behavior [74].

Biology and Digital Technology: Cooperation or Conflict?

It seems inevitable that digital and biological information will become more integrated in the future. This scenario raises the question of how such an organic–digital fusion might become a symbiosis that coevolves through natural and artificial selection. In all symbioses, there is potential for exploitation and cheating [75], and this possibility has to be examined for the biological–technological fusion. Science fiction has frequently examined conflicts that end in either the extinction or parasitism of the human species and intellectuals from Stephen Hawking and Noam Chomsky to Bill Gates and Elon Musk have all warned about the existential threat posed by AI [76,77].

One widespread scenario is based on the idea that the Internet will become self-aware [78], but this philosophical concept is not necessary. The ability of AI to make high-quality decisions, and to do so in a manner that may not be aligned with human values, is the major concern. The priority of AI to assure its own continued existence need not stem from conscious self-interest but may simply be a result of high-quality decisions aimed at succeeding with an assigned task in a consistent manner. The decision-making capabilities of AI can affect billions of computers and most of humanity's infrastructure. Such decisions might come with irreversible impacts [10].

In a fusion of digital and biological systems, both could contribute their functions to generate a higher unit of organization, similar in effect to previous evolutionary transitions [43]. Such a transhuman vision is referred to as the technological singularity [79]. While speculative future visions of the singularity include nanobots in cerebral capillaries that connect the brain with the digital cloud [80], humans already embrace fusions of biology and technology. We spend most of our waking time communicating through digitally mediated channels, it is common practice to convert deaf children into functional cyborgs using cochlear implants [81], we trust artificial intelligence with our lives through antilock braking in cars and autopilots in planes, most transactions on the stock market are executed by automated trading algorithms [82], and our electric grids are in the hands of artificial intelligence [83]. With one in three marriages in America beginning online [84], digital algorithms are also taking a role in human pair bonding and reproduction.

Symbiosis between the biological and the digital may sidestep the slow pace of natural selection and evolution. It has been suggested that there are energy and infrastructural constraints that ultimately govern human brain size and activity [85] and that our brain size may be approaching the evolutionary limits of cognitive power [29]. Given that physical restrictions may prevent evolutionary improvements in cognition, the integration of biological with digital processing and information storage is one way forward.

Technological progress shows signs of being superexponential when examined across technological paradigms [86]. New computational platforms, from nanotechnological modeling of neurons [87] to developments in quantum computing [88], provide justification that artificial processing might maintain its exponential growth even beyond its silicon basis. In theory there are 10^{90} bytes stored in the observable universe [89], providing ample room for expansion of the computational capacities of life as a whole.

Concluding Remarks

We argue that we are already in the midst of a major evolutionary transition that merges technology, biology, and society. From personal experience, our daily lives are full of examples of our synergistic cooperation with the digital organism [90]. From a social perspective, digital technology has infiltrated the fabric of human society to a degree of undisputable and often life-sustaining dependence. Scholars of ecology and evolution should join the debate and seriously and systematically think about the consequences of digital information for the trajectory of life.

Outstanding Questions

Can accumulation of digital information continue at its present superexponential rate?

When will the amount of digital information exceed that of DNA information in the biosphere?

What are the similarities and differences between evolutionary processes in digital and nucleotide-based information?

What are the possibilities for humans to expand cognition by direct connection to the Internet?

Is it possible for portions of the Internet to become self-replicating?

Are there potential dangers arising from the digital information explosion?

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