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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,