Time, evolution and physical reductionism

The arrow of evolutionary time challenges an eventual physical theory of everything

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The experience of time is familiar to us all, yet it remains one of the greatest scientific mysteries. For centuries, physicists and philosophers have puzzled over the nature of time, or even whether it exists at all. Is time a real, physical entity or a construction of the human mind? How did time start and where does it come from? Will it ever end and what came before it? For physicists, the answers to these questions are relevant in their work to develop a theory of everything (TOE), the aim of which is to explain all particles and forces of nature. At present, the main handicap for a TOE is the incompatibility between predictions made by Einstein's theory of general relativity and those of quantum mechanics [1]. Relativity is useful to understand gravitational force, which governs large-scale mass interactions, whereas quantum physics deals with the other three basic forces of nature: electromagnetic force, and strong and weak nuclear forces, which are involved in atomic and subatomic interactions. A recent attempt to unify both theories into so-called string theory has been received as a good candidate for a TOE, but it is not universally accepted as a cosmological model [2].

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Ideally, a TOE should be a perfect model of reality; a complete and consistent set of fundamental laws of the universe that could be used to predict all phenomena [2,3]. So far, most attempts to formulate a TOE have been intrinsically reductionist,

because they are based on the fact that any system in the universe is made of the same fundamental physical entities and, as such, are subject to the same fundamental laws. This context either totally ignores life and evolution or implicitly regards these as a default. However, further analysis shows that this ignorance of the living world is not a prudent approach to understanding the universe.

Evolutionary biologist Ernst Mayr believed that several concepts in physics—essentialism, determinism and reductionism—are mostly not applicable to biological systems. Essentialism (or typology) posits that there are a limited number of natural kinds, called essences or types, each forming a class. The members of each class are thought to be identical, constant and sharply separated from the members of any other class. Typological thinking is unable to accommodate intermediate states and variation, two integral features of biological entities, which are considered nonessential and accidental.

Determinism, as espoused by the French mathematician Pierre-Simon Laplace, who claimed to be able to predict the future to infinity from a complete knowledge of the present, is incompatible with the contingent nature of biological processes, in which chance, stochasticity and chaotic behaviour are common.

Reductionism, or the idea that a complete inventory and precise knowledge of each component of a system are enough to explain the system and its functioning, is not applicable to biological systems either because of the existence of new, unpredictable

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(emergent) properties at each level of evolutionary integration [4]. Contrary to physics and chemistry, these emergent properties derive not only from chance, but also from the nature of biological systems themselves. Indeed, living beings have unique capacities that are not present in the inanimate world: self-replication, growth and differentiation through a genetic programme, metabolism, self-regulation to keep the system in homeostasis, responding to stimuli from the environment, change at the phenotype and genotype levels, evolution and mortality. These features can be more broadly described by two characteristics: high complexity and evolution.

The basic difference between living and non-living things is that biological processes are subject to dual causation; that is, they are controlled not only by natural laws, but also by genetic programmes. These genetic programmes are the raw material for biological evolution. There is nothing comparable to this in the inanimate world [4].

These biological capabilities are the reason for the fundamental differences between physical and biological processes in time. One example is the thermodynamic meaning of evolution, as compared to physical systems, for which it is necessary to introduce the concept of

time's arrow (TA). In spite of the fundamental uncertainties about time, evidence for its existence can be found in many processes, from cosmological to psychological ones. These processes have in common that they allow us to distinguish the past from the present in a continuous, directional and irreversible fashion, thus defining a TA.

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Using Ludwig Boltzmann's interpretation of the second law of thermodynamics, one definition of a fundamental cosmological TA proposes a universal, continuous and inexorable increase of entropy. This concept of time, known as the thermodynamic or pessimistic TA, predicts the end for the universe by thermal death [5]. By contrast, cyclic time has no direction; fundamental states are imminent in time, always present and never changing. In cyclic time, apparent progress is part of ever repeating cycles, and differences of the past will be realities of the future [6]. Physical examples of cyclic time are the movement of subatomic particles and celestial dynamics that follow classical Newtonian mechanical laws.

The evolution of life on Earth has characteristic features—continuity, directionality and irreversibility—that provide empirical evidence of a directional TA, an evolutionary TA (eTA). The fossil record shows that evolution has continued since life began at least 3.8 billion years ago [7]. The emergence of life itself is probably the result of a trial-and-error process, which means that evolution took place even before the first primitive cell: evolution therefore preceded life [8]. Evolution is also directional, as manifested by the progressive increase in the diversity and complexity of organisms and the communities they form; from unicellular prokaryotes to higher organisms, and from the simple stromatolitic producer-decomposer organization to the complex communities that are tropical rainforests or coral reefs. This directionality involves not only an increase in organismal diversity and complexity, but also in the number and complexity of biotic and abiotic interactions, with corresponding effects

on matter interchange and thermodynamic processes. Such directionality, however, does not mean that evolution is a teleological process [4], as the stochastic elements involved in both biological processes and environmental forces produce unpredictable results. The fossil record also shows that evolution is irreversible, as the emergent life forms are always new and different without recurrences [9].

Evolution also has cyclic components, but these do not break the directionality of the eTA; rather, they contribute to irreversibility. Examples of this duality are homologies and analogies in organisms [6]. Homologies arise from a common ancestor and represent eTAs. An example of a homology is the backbone, which has undergone irreversible modifications from the first primitive vertebrates to today's mammals along a unique and continuous evolutionary line.

Analogy appears in genealogically distant lineages of organisms and is often associated with particular environmental adaptations. Well-known examples are the wings of insects, birds or bats, the ontological origins of which are totally different. Analogies are considered manifestations of cyclic evolution, as they reappear at different stages of the whole tree of life but in totally different organisms. The American evolutionary biologist Stephen J. Gould, for instance, discussed the example of the fins of the ichthyosaur, a descendant of terrestrial reptiles that returned to the sea during the Jurassic period. This 'sea lizard' had dorsal and caudal fins analogous to those of fish—they evolved independently between these groups—while the ventral fins are homologous to, that is, modified from, the legs of its terrestrial ancestor. This combination of homologies and analogies in the same organism creates new life forms and therefore contributes to evolutionary unpredictability and irreversibility [6]. Another example of cyclic phenomena comes from molecular phylogenetics. Fossils can only show us some phenotypical expressions of their host genomes, but the study of the genome itself can reveal how some mutations have arisen

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several times at the same locus before becoming fixed [10].

Cyclic phenomena sometimes drive directional evolution. Cyclic variations in the Earth's orbital parameters, such as eccentricity, obliquity and precession—the Milankovitch cycles—influence global climate and correspondingly the biosphere. These cycles have occurred since the early Palaeozoic, around 500 million years ago [11]. The more recent and well-documented manifestations of their impact are the Pleistocene glaciations, which started 2.5–3 million years ago. Their evolutionary significance has been extensively discussed, and molecular phylogenetics has revealed intense evolutionary activity during the past 3 million years. This activity is thought to reflect an increase in speciation owing to the continuous and recurrent creation and destruction of geographical bridges and barriers during periodic climatic shifts [12].

On a larger scale, mass extinctions are recurrent, possibly cyclic events that have dramatically changed the evolutionary process. The biggest mass extinction documented so far was at the end of the Permian, about 250 million years ago, and is thought to have eliminated around 95% of the species on Earth [13]. However, each mass extinction has triggered spectacular bursts of diversification from a few survivors. This means that the principal eTA has not been broken and that there is only one single tree of life on Earth. Mass extinctions and the subsequent diversification imply that many evolutionary lines have been interrupted while others continued on, thus creating new evolutionary opportunities. Both extinction and evolutionary continuity have occurred randomly and independently in different lineages, adding even more stochasticity and contingency to the evolutionary process.

The eTA is therefore a highly unpredictable trend, as a manifestation of a stochastic and contingent process, from simpler to more complex forms and with increasing levels of organization and emergent properties. It is a constructive or progressive trend that does not follow the assumedly universal rule of thermodynamic degradation, which is a destructive process—the eTA has therefore been called the optimistic TA [14].

The second principle of thermodynamics was proposed in the late nineteenth century by physicist Rudolf Clausius, one of the founders of thermodynamic science, who

studied closed systems that did not exchange energy or matter with their environment. In contrast to Clausius's closed systems, living systems are open, dissipative systems that permanently swap matter and energy with their environment and are always far from thermodynamic equilibrium: that is, death. In this sense, life seems to be a permanent struggle against thermodynamic equilibrium. Therefore, one possibility is that the law of entropy is not applicable to biological systems and their evolution [4].

Several efforts have been made to solve this problem, including early attempts by physicists Ludwig Boltzmann and Erwin Schrödinger, who proposed that organisms are able to maintain large amounts of order within the generalized disorder of the environment, but that this capacity does not violate the second principle as it only represents a delay in the eventual increase in entropy. A milestone was the proposition of the self-organization theory by Ilya Prigogine and colleagues, for which they received the Nobel Prize in 1977. The idea

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of self-organization is that order might spontaneously emerge from chaos in an irreversible fashion: a system that is not in thermodynamic equilibrium can reach a state of higher complexity and a high level of order, and requires higher amounts of energy from the environment to persist [15]. In this way, the system generates an irreversible process towards progressively increasing diversity, complexity and matter/energy, as exhibited by biological evolution for open dissipative systems. Experiments have shown that self-organization can create progressively ordered and complex structures, but its eventual ability to reproduce biological evolution has yet to be demonstrated.

Among the biological features that could be explained to some extent by self-organization processes are morphological

(phenotypic) change through time [16] and the emergence of complex ecosystems [17]. However, these processes seem to be unable to capture the genetic basis of evolution [16], the most important feature that distinguishes inanimate things and the living world. Furthermore, inferences from self-organization are based on mathematical models—after all, self-organization itself is a mathematical artifice—with relatively poor validation against nature, which restricts its applicability. Johan van der Koppel [18], an ecologist working on spatial self-organization, believes that “the topic of complexity in ecology is in its current state mostly about the complexity of models rather than of the natural world”. Regardless, self-organizational processes might well have been important during the initial pre-biotic phases that preceded the formation of the first living cells [19]. Pre-biotic processes were essentially chemical transformations leading to organic molecules, a process known in chemistry as self-assembly, which is equivalent to self-organization.

It therefore seems that the eTA is different from the thermodynamic TA, which implies that the latter would not be valid for every phenomenon. This would prevent any eventual TOE based solely on physical processes. The properties and behaviours of organisms, including human beings, and their evolution, are not predictable from the properties of their constituents; therefore, any candidate TOE must account for biological complexity, contingency and emergent properties [20]. If such a TOE is possible, it should arise from the study of the complexity and evolution of living systems and their description in general terms, not from forcing complex systems to obey physical laws. Indeed, some contemporary physicists, including Stephen Hawking, think that to understand the universe, we might need different theories in different situations, each one with its own version of reality and none more real than any other [3]. Others support the idea that owing to contingency and the existence of emergent and unpredictable properties and processes, the understanding of the universe needs a plural scientific approach, and that scientific knowledge cannot be restricted to general models [21]. In other words, there is no such thing as a TOE, or if there is, it is subjective [2].

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In the context of the present discussion, the discovery or not of life on other planets would challenge the assumed universal physical and/or biological laws. If life is exclusive to Earth, it could be a universal anomaly and not a cosmic imperative and therefore challenge a physical TOE. Whether extraterrestrial life exists is a question beyond the scope of this paper, and any discussion on the subject is purely speculative. But let us assume for a moment that we are not alone in the universe, just to see where this speculation would lead. A fascinating question is whether there is one single universal tree of life or not [22]. The same tree of life cannot have originated on more than one planet; therefore, if it is unique and universal, the more likely explanation would be that life was transported between planets via meteorites or

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by other means, a hypothesis often called panspermia. At present, there are few interplanetary meteorites or other structures, but they must have been far more frequent during the formation of the planets [23]. If life was transported between planets, there could be as many eTAs as there are inhabited planets, as evolution would have proceeded differently on each planet owing to their respective special features and geological history, evolution's intrinsic stochastic and contingent character, potential differences in the time of origin or inoculation, and the nature of the transported inoculates. Alternatively, if life arose independently on different planets, which means that there is more than one tree of life, it is possible that the underlying biochemistry of life is either the same as on Earth—carbon-based, with DNA as the carrier of genetic information—or not [24]. In both situations, planetary peculiarities would have shaped the final result, although in the latter case the evolutionary patterns and outcome would be even more unpredictable.

Respective of whether there is one or more tree of life in the universe, every host planet would have unique eTAs, reflecting each planet's particular features. In other words, evolutionary time would be planetary-dependent, and a unique universal eTA would be unlikely—although the eTAs would be parallel. Thus, even if life is a widespread phenomenon, evolutionary characteristics are not expected to be uniform throughout the universe, one more handicap for a TOE. Of note, there has also been speculation about the possibility of more than one tree of life on Earth itself [25]. There might well be a 'shadow biosphere' [26] in the still largely unknown microbial world if life on Earth originated more than once. It would be an interesting case of two or more trees of life subjected to the same planetary constraints.

An answer is not easy to find and is hardly attainable from a reductionist versus non-reductionist debate. Rather than perceiving life and its evolution as inconsistent with current physical theories, they should

be regarded as an opportunity to enhance our knowledge of the universe and identify new, more general laws. Ideally, multi-disciplinary teams should address this intellectual challenge. So far, scientific disciplines—for example, physics and biology—have been so disconnected that a proper comprehension of each other's foundations, interests, methods, principles or paradigms has been almost impossible. Perhaps the field of molecular biology, in a wide sense, could provide a suitable arena for discussions, given its transitional and multidisciplinary nature.

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CONFLICT OF INTEREST

The author declares that he has no conflict of interest.

REFERENCES

1. Duff M (2011) Theory of everything: the big questions in physics. *New Sci* **210**: ii–iii
2. Hutter M (2010) A complete theory of everything (will be subjective). *Algorithms* **3**: 329–350
3. Hawking S, Mlodinow L (2010) The (elusive) theory of everything. *Sci Am* **303**: 68–71
4. Mayr E (2004) *What Makes Biology Unique? Considerations on the Autonomy of a Scientific Discipline*. Cambridge, UK: Cambridge University Press
5. Drory A (2008) Is there a reversibility paradox? Recentring the debate on the thermodynamic time arrow. *Stud Hist Philos Mod Phys* **39**: 889–913
6. Gould SJ (1987) *Time's Arrow, Time's Cycle: Myth and Metaphor in the Discovery of Geological Time*. Cambridge, MA, USA: Harvard University Press
7. Mojzsis SJ, Arrhenius G, McKeegan KD, Harrison TM, Nuyman AP, Friend CR (1996) Evidence for life on Earth before 3,800 million years. *Nature* **384**: 55–59
8. Tessera M (2011) Origin of evolution versus origin of life: a shift of paradigm. *Int J Mol Sci* **12**: 3445–3458
9. Coyne JA (2009) *Why is Evolution True?* New York, NY, USA: Viking
10. Page DM, Holmes EC (2003) *Molecular Evolution: a Phylogenetic Approach*. Malden, MA, USA: Blackwell Science
11. Bennett KD (1997) *Evolution and Ecology: the Pace of Life*. Cambridge, UK: Cambridge University Press
12. Rull V (2011) Neotropical biodiversity: timing and potential causes. *Trends Ecol Evol* **26**: 508–514
13. Benton MJ, Twitchett RJ (2003) How to kill (almost) all life: the end-Permian extinction event. *Trends Ecol Evol* **18**: 358–365
14. Halpern P (1990) *Time Journeys: a Search for Cosmic Destiny and Meaning*. New York, NY, USA: McGraw-Hill

15. Prigogine I, Stengers I (1984) *Order Out of Chaos: Man's New Dialogue with Nature*. Toronto, Canada: Bantam Books
16. Stewart I (2003) Self-organization in evolution: a mathematical perspective. *Phil Trans R Soc Lond A Phys Sci* **361**: 1101–1123
17. Solé RV, Bascompte J (2006) *Self-Organization in Complex Ecosystems*. Princeton, NJ, USA: Princeton University Press
18. Van der Koppel J (2007) Book review: Self-organization in complex ecosystems. *Monographs in Population Biology* 42. *Math Biosci* **212**: 109–110
19. Pulselli RM, Simoncini E, Tiezzi E (2008) Self-organization dissipative structures: a thermodynamic theory for the emergence of prebiotic cells and their epigenetic evolution. *Biosystems* **96**: 237–241
20. Dolsenhe O (2005) *A Genuine Theory of Everything*. Houston, TX, USA: Bookstand Publishers
21. Ziman J (2003) Emerging out of nature into history: the plurality of the sciences. *Phil Trans R Soc Lond A Phys Sci* **361**: 1617–1633
22. McKay CP (2011) The search for life in our solar system and the implications for science and society. *Phil Trans R Soc Lond A Phys Sci* **369**: 594–606
23. Pace NR (2001) The universal nature of biochemistry. *Proc Natl Acad Sci USA* **98**: 805–808
24. Benner SA, Ricardo A, Carrigan MA (2004) Is there a common chemical model for life in the universe? *Curr Opin Chem Biol* **8**: 672–689
25. Cleland CE, Copley SD (2005) The possibility of alternative microbial life on earth. *Int J Astrobiol* **4**: 165–173
26. Davies PCW (2011) Searching for a shadow biosphere on Earth as a test of the 'cosmic imperative'. *Phil Trans R Soc Lond A Phys Sci* **369**: 624–632

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