# Biological Emergence: a Key Exemplar of the Open Systems View

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## Abstract

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The context for biological emergence is modular hierarchical structures; their existence is what enables functional complexity to arise. Because of the openness of organisms to their environment, complete initial data (position, momentum) of all particles making up their structure is insufficient to determine future outcomes, because unpredictable new matter, energy, and information impacts each organism from the exterior. Consequently, through Darwinian evolution, life has developed processes to handle this issue functionally on short time scales as well on longer developmental timescales. Symbolism and technology are the transforming factors handling this issue at the social levels, which is where the most sophisticated outcomes of openness occur. Considering the cosmological context, the issue is, should the universe itself be regarded as an open system over time? I make the case that is indeed so, because radically new outcomes occur such as the existence of aircraft, iPads, and the internet, which could not plausibly have been encoded in some form of data on the Last Scattering Surface in the expanding universe.

**1: Introduction**

Because each organism is finite with a boundary, all biological entities are open systems (von Bertalanffy 1950, Peacocke 1989), with forces, matter, energy, and information impacting on them from the surrounding environment. They respond reciprocally by impacting on the environment in each of these ways. Because organisms carry out a variety of functions (Hartwell *et al* 1999, Ball 2023), the Second Law of Thermodynamics implies they must use energy and materials in order to do so, obtained by interactions with the environment. These exchanges across the organism's boundaries are carefully controlled by physiological mechanisms at each emergent level. This chapter discusses how that happens.

Consequent on this openness, unpredictable external events impact on an organism, so it's future behaviour cannot be fully determined by dynamical development from its initial internal state. To enable survival, true emergence must occur to cope with this situation, where (without making any metaphysical claims) by "true emergence" I mean novel and robust behaviour at emergent levels. The organism must be capable of flexible adaptive responses to incoming influences, particularly by homeostasis and metabolic processes. Furthermore higher-level organisms greatly enhanced survival prospects by developing memory-based agency (Humphrey 2022, Mitchell 2023, Corning *et al* 2023), allowing predictive processing of incoming data regarding the changing external context, and so intelligent choice of actions.

The broad framework for this chapter is that set out in Table 4 of the paper "Toward a conceptual framework for biology" (Scheiner 2010) as follows (TABLE 1). Item 1is the central theme that I develop here. Items 2-8 are the keys allowing this to happen, with 9 and 10 providing context.

| **Domain** |
|---|
| The diversity and complexity of living systems, including causes and consequences. |

| **Principles** |
|---|
| 1. Life consists of open, non-equilibrium systems that are persistent. |
| 2. The cell is the fundamental unit of life. |
| 3. Life requires a system to store, use, and transmit information. |
| 4. Living systems vary in their composition and structure at all levels. |
| 5. Living systems consist of complex sets of interacting parts. |
| 6. The complexity of living systems leads to emergent properties. |
| 7. The complexity of living systems creates a role for contingency. |
| 8. The persistence of living systems requires that they are capable of change over time. |
| 9. Living systems come from other living systems. |
| 10. Life originated from non-life. |

**TABLE 1: The domain and fundamental principles of the theory of biology (**Scheiner 2010).

The aim of the chapter is to clarify the consequences of this openness of biological systems.

The following sections of this chapter look at, §2: The context: modular hierarchical structures; which is what enables complexity to arise; §3: The insufficiency of initial internal data to determine organismal outcomes, which is the key feature arising because of this openness; §4: Processes to handle this issue functionally on short time scales: §5, Processes to handle this issue on developmental and evolutionary timescales, which are much longer periods that set up the basis for the shorter ones; §6: Symbolism and technology: the transforming factors at the highest levels, which is where the most sophisticated outcomes of openness occur; and §7: The cosmological context, where the issue is, should the universe itself be regarded as an open system over time.

2: **The context: modular hierarchical structures**

For good functional and evolutionary reasons, all truly complex systems, including life, are organised systems (Mossio 2023) that are adaptive modular hierarchical structures (Booch 1990, Simon 1996, Ellis 2016, Ellis and Di Sia 2023). The levels and details of the biological hierarchy are presented in depth in Campbell and Reece (2005). We can represent them, including the astronomical context, as in Table 2.

| | | |
|---|---|---|
| L14 | Cosmos | |
| L13 | Our Galaxy, Andromeda Galaxy | |
| L12 | Solar system | |
| L11 | Biosphere, International systems | |
| L10 | Ecosystem, Nation | |
| L9 | Population, Society | |
| L8 | Organism, Person | |
| L7 | Physiological systems | |
| L6 | Tissues | |
| L5 | Cells | |
| L4 | Organelles, subcellular machinery | |
| L3 | Macromolecules | |
| L2 | Atoms | |
| L1 | Particles (protons, neutrons, electrons) | |

**TABLE 2: The hierarchical structure of biology in its astronomical context.** *Each higher level is the context for the next level down. Interlevel causation takes place as indicated by the arrows. The astronomical context is levels L12-L14. The arrows indicate the interlevel causation taking place.*

There are physical levels below level L1, but they do not matter as far as biology is concerned, because of the existence of classical and quantum protectorates (Laughlin and Pines 2000). Whatever their nature,

which is only partially known, they lead to emergence of physical Levels L1-L2 as experimentally verified (Leighton and Sands 1965). Carroll (2021) makes a similar point, based on effective field theory methods.

At each level below L14, one has spatially finite systems that interact with other systems at the same level (thus being open systems). The scale of the higher level open systems is larger than that of each of the lower level ones. They emerge upwardly from lower-level systems as indicated by the upwards arrows, and influence lower levels as indicated by the downward arrows by either setting boundary conditions and constraints (Juarrero 2000, 2023, Noble 2002, 2008, 2012, 2016), or by creating, altering, or deleting lower-level elements (Ellis 2023). Thus each level is open relative to both the levels above them and below them, as well as to systems at the same level. Level L5 is the lowest one where all the functions of life occur (Mukherjee 2022): cells are open non-equilibrium systems (Von Stockar 2013).

The biosphere (Level L11) is also open, driven by incoming high-grade solar radiation from the sky (L12 ➔ L11) which provides its power source, and radiating low-grade radiation back to the sky (L11➔ L12). The low temperature of the sky enabling this is an outcome of the dynamical expansion of the universe, whereby the temperature of Cosmic Blackbody Radiation emitted at the Last Scattering Surface at 4000K billions of years ago has decreased to 2.73 K today (Peebles 2020).[1] Thus the sky acts as a heat sink for the Solar System and for all biological systems on Earth. Graham (2023:65) explains "*If the whole sky was as bright as the Sun, there'd be abundant energy but no gradient, and no possibility of an engine"*. This openness to the universe (L11 ➔ L14) is thus key to the functioning of the Sun and the biosphere in thermodynamic terms.

At a fundamental level, existence of all the emergent levels L2 – L11 is due to the occurrence of broken symmetries (Anderson 1972, Zangwill 2021), which frees those higher levels from obeying the symmetry groups governing special relativity and particle physics (Levels L1 and below). The boundaries defining an open system break these symmetries, as do their internal structures.

**3: The insufficiency of initial data to determine organismal outcomes**

The future behaviour of an organism cannot even in principle be uniquely determined by dynamical development from its internal state $\mathbf{S(t_0)}$ at any initial time $t_0$, where $\mathbf{S(t_0)} = \{\mathbf{x}_I(t_0), \mathbf{p}^I(t_0)\}$ specifies the position $\mathbf{x}_I$ and momentum $\mathbf{p}^I$ of every particle **I** in the organism's brain. This is the data required by Laplace's Demon to determine its future brain state from the relevant dynamical equations – Newton's law of motion, Maxwell's equations, the diffusion equation, and so on.[2] The

[1] The existence of a dark night sky is known as "Olber's Paradox": Bondi (1960), Harrison (1965, 1974).
[2] Quantum dynamics will only indirectly influence what is going on, because there is no wavefunction for a cell or a brain: see Ellis (2024). Classical physics is sufficient for this discussion, even though quantum physics adds extra uncertainty to physical outcomes.

essential point is that external events will occur that are not described by the data $\mathbf{S(t_0)}$ – a nearby car crash, tidal wave, tornado, the approach of a threatening dog or person, offer of a free holiday in Majorca, and so on. These require a suitable response – fight, flight, accept or reject an offer, and so on. The required brain micro-states $\mathbf{\{S(t): t> t_0\}}$ needed for appropriate responses to such external events at times $\mathbf{t > t_0}$ are simply not available to the organism on the basis of $\mathbf{S(t_0)}$ alone, because they omit all data about all such external influences that may impact the organism after the time $\mathbf{t_0}$. These continually change the context of needed actions, and hence alter brain functioning.

True emergence (as defined above) must occur to cope with this situation. In order to react appropriately to such unpredictable incoming influences, as is needed to survive, the organism must be capable of adaptive predictive responses. Higher level organisms therefore evolved sentience (Humphrey 2022) and agency (Mitchell 2023) to allow this kind of response, including the capacity of humans for predictive processing of likely outcomes (Hawkins and Blakeslee 2004, Clark 2013) and hence intelligent choice of actions. Furthermore, being an open system, any organism will from time to time experience hotter or colder conditions that must be adjusted to; the need for shelter if it rains or snows; dodging falling objects from trees or tidal waves from the sea; and so on. Thus all organisms must be able to adapt to such changes in their surroundings, which are not determined by the state of all the particles in their bodies at an initial time $t_0$. They must have agency enabling adaptive responses to such events that affect them at later times. The Laplace's Daemon argument fails to take into account spatial boundedness and openness. Indeed, the Laplacian conception of determinism is supposed to apply ***only*** to closed systems, i.e., if the system is closed (and the laws are deterministic), then we can predict its future from its initial state with certainty. So the Laplacian agrees with the contrapositive: if we can't predict the future state of the system from its initial state (and if the laws are deterministic), then the system is open.[3]

Furthermore, the total set of particles $\boldsymbol{P(t)}$ that makes up the organism at time $\boldsymbol{t}$ will itself be different at a time $\mathbf{t_1 > t_0}$ than at an initial time $\mathbf{t_0}$ as some new particles will have been taken on board by breathing, drinking, and eating, and some will have been got rid of by breathing, sweating, and excreting. The set of particles $\boldsymbol{P(t_1)}$ making up the organism at time $\mathbf{t_1}$ is not the same as the set of particles $\boldsymbol{P(t_0)}$ making up the organism at time $\mathbf{t_0}$, and this later set of particles is not predictable from that initial state, which depends on the changing state of the environment (atmospheric pollution or eating at a restaurant, for example). Thus the context for Laplace's demon for the organism as a whole to function is simply not there. The relevant particles are different, and the state space has changed. This is a central consequence of living systems being open systems. In Aristotelian terms, it is a form of time dependent material causation (Ellis 2023).

[3] I thank a referee for this comment.

Thus in the case of any open system, neither the information nor the material particles are available within the system for Laplace's demon to begin to operate on and determine the future of that system from its initial state. Something else is going on.

**4: Processes to handle this issue functionally**

To handle these problems of dealing with unknowable incoming data and material on functional (short) timescales, the organism needs metabolic systems and homeostasis. It will be much more successful if it has the capacity for predictive processing, and preferably agency, as in the case of fish, octopuses, lobsters, birds, rodents, mammals including human beings – where planning and action selection can take place, and reciprocally shape the effects of the organism on the exterior environment, which in turn alters future environmental effects on the organism.

**Metabolic systems** handle taking in new material (solid, liquid, and gaseous) and transforming them into usable forms for functional purposes, moving them to where they are needed in the body, and then removing waste products and disposing of them. This happens in a coordinated way at each emergent level. Food ingested at the physiological level via the digestive system is made of biomolecules that are transformed to useful forms via enzymes at the cellular level, then transported via the cardiovascular system to where they are needed. The digestive systems gets rid of waste products (urine and faeces). Because specific proteins are needed to make this happen, metabolic and gene regulatory networks work in an integrated way (Goelzer *et al*. 2008, Sauer and Teusink 2018). Underlying all this is the second law of thermodynamics: using energy for some purpose transforms useful stuff to unusable waste and generates entropy. Each cell is an open system that therefore needs nutrients to stay alive (van Stockar 2013, Mukherjee 2022), and uses energy in the form of ATP supplied by the citric acid cycle (Akram 2014). Ingress and egress to the cell is tightly controlled by voltage gated and ligand gated ion channels, which enable logical branching to emerge from the underlying physics (Ellis and Kopel 2019). This is a key link between physics and biology, enabled by cells being open systems. Metabolic processes occur via physiological systems such as mouth and nose and lungs and stomach and excretory systems at the macro scale, together with metabolic cycles within cells at the micro scale (Cabrera *et al* 1998). The interaction with the environment is carefully controlled at each level in this way.

As far as the brain itself is concerned, there is a rapid turnover of brain molecules: indeed circuit-specific protein turnover is thought to underlie synaptic plasticity (Mohar *et al* 2022). You simply are not dealing with the same molecules at later times than earlier times. However the turnover takes place so that molecules are replaced one at a time without altering the state of the

emergent structure (Crick 1984, Lee *et al* 2022); in this way memory is preserved during these processes. Problems arise when this process starts to falter with aging (Rao *et al* 2024).

**Homeostasis** is a mechanism for dealing with unpredicted incoming influences of an expected nature - they have been encountered before in our evolutionary history. It involves stabilising mechanisms enabling the system to respond appropriately to perturbations of a type often encountered by using an error signal (the difference between the current state and the desired state) to activate mechanisms that will change the situation back to the desired state (Cannon 1929, Modell *et al* 2015). There are numerous feedback loops in the human body at both macro and micro levels, controlling blood pressure, temperature, heart rate, electrolyte levels, ion levels in cells, and so on (Guyton and Hall 2006, Hall and Hall 2020). You are ill if any of them are out of bounds.

Homeostatic systems can be adaptive in nature (Davies 2016). They can be taken to include the innate and adaptive immune systems (Parkin and Cohen 2001, Flajnik and Kasahara 2010), the latter dealing with the crucial issue of keeping healthy despite viruses of many unknown kinds invading the body unpredictably from the exterior. The immune systems are quintessential responses to the problem of the human body being an open system. Again outcomes are not predictable from prior knowledge of the state of all molecules in the body: the unpredictable incoming pathogens, as well as immunisation programs instituted by health authorities to counter them, play a key role in shaping health and physiological outcomes at later times.

**Agency** allows a major advance in dealing with these issues, because it is the way we can handle completely unexpected events in a suitable way. Thus there has been strong evolutionary pressure for it to come into existence (Humphrey 2022, Mitchell 2023). This enables planning to meet new challenges from outside not merely when they are perceived but when they can be predicted, even if they have never happened before. In humans it becomes effective in the context of a system level architecture for cognition, emotion and learning (Franklin *et al* 2013, Franklin *et al* 2016).

**Information processing and the brain** Information process is central to biology (Farnsworth *et al* 2013, Nurse 2008), and of course in the functioning of the brain (Churchland and Sejnowski 1999), allowing higher levels of agency. Ongoing functioning of the brain at macro and micro scales enables appropriate responses to the ever-changing current situation in the physical and social environment. We interpret incoming information through predictive Bayesian brains (Clark 2013). Their state is updated on an ongoing basis as new data arrives via our various senses, filtered by cortico-thalamic feedback circuits (Alitto and Usrey 2003). Markov blankets act as an interface (Clark 2017) allowing minimisation of surprisal as we apprehend and then react to changes affecting us (Friston and Stephan 2007). The brain changes physically as this takes place at both macro and micro scales: this

is brain plasticity (Kandel and Hawkins 1992, Kolb and Whishaw 1998), whereby we in a sense embody an image of the outside world in the details of our cortical connections. Memory of past events structures a mental model of the environment in which the organism is based, enabling predictions of future interactions and events (Hawkins *et al* 2009). Off-line analysis on the basis of internal models enables planning of future actions in an anticipatory way (Mitchell 2023). This leads to mental causation occurring (Murphy and Brown 2007, Robb and Heil 2021) and affecting the outside world, which cannot uniquely anticipate what that action will be. Unpredictability across the organismal boundary goes both ways.

A key aspects of this is interaction is the development of a Theory of Mind by each of us (Frith and Frith 1999, 2005), enabling appropriate navigating of social contexts. This internal model will be changing on a minute-by-minute basis as we interact socially and perceive social clues (Frith 2007).

At the mental level, humans are capable of imagination (Warnock 1976) that totally transforms outcomes of this processing: what the mind comes up with can be unlike anything that has ever existed before (iPhones, the internet, etc). In that sense, the mental world is not a closed system: it can expand to include anything that is possible, thus transforming technology and society.

**Interlevel integration** These processes take place at each level in Table 2. They have to be integrated so that the higher-level needs are fulfilled via the lower-level functions, and the lower level functions are enabled to function as needed via the higher level context. This integration must take place on an ongoing basis. This adaptive process at the mental level involves downward selection of desired lower-level states on the basis of higher level needs (Noble 2021, Noble and Noble 2021), enabled by the huge stochasticity at the molecular and cellular level (Mitchell 2018, Ball 2022, Graham 2023) that allows such adaptive selection (Mitchell 2023). Causal closure only occurs when all interacting levels are taken into account (Ellis 2020).

**5: Processes to handle this issue on developmental and evolutionary timescales**

The organism needs developmental systems to bring it into being from a single cell (Wolpert *et al* 2002). These are provided by gene regulatory networks interlocking with metabolic systems which are read in a contextual way (Oyama et al 2003, Griffiths and Gray 2005): genes and environment interact in complex feedback loops during development. The process of natural selection (Darwin and Wallace 1958) involves genetic mutations through various causes and then selection of those organisms with relatively higher reproduction rates leading to more fit organisms, all mediated by the inherited information transmitted to our offspring through our genes (Mitchell 2018, 2023). We inherit also DNA methylation, cellular machinery, and culture, as well as genes. Furthermore organisms construct their own niches, introducing evolutionary feedback loops: as open systems, the ecological context affects

the organism and vice versa in a reciprocal way. The time development of each is reliant on the other. because of their interactions. Neither is determinate on its own.

Evolution and development are integrated with each other to form EVO-DEVO processes (Carroll 2005, 2008), so they should properly thought of as taking place together - although they are of course only possible through minute by minute functional processes as just discussed, so in fact all three occur together. But the key point is that it is the evolutionary processes that allow adaptation of the organism, more or less successfully, to the physical, biological, and ecological environment. This is a crucial case of downward causation (Campbell 1974, Murphy and Brown 2007) in response to the organism being an open system subject to influences from these environments, where by "downward causation" I mean higher levels affecting conditions at lower levels in a reproducible way, this being demonstrated either counter-factually or experimentally.

All the levels in Table 2 must be simultaneously adapted in an integrated fashion as the animal interacts with its environment on developmental and functional timescales, and as the population interacts with its environment on ecological and evolutionary timescales. Downward causation takes place from context **L10** to **L9** and **L8**, and then chains right down to the molecular level of genes and proteins (Wagner 2014) and the underlying physics levels.

**6: Symbolism and Technology: the transforming factors on the highest levels**

Humans are a symbolic species (Deacon 1998). Individuals are open systems, interacting to create a society (Berger 1963). Our interactions with each other led to the development of language that transformed our lives by enabling communication of ideas, plans, and feelings in sophisticated ways. Furthermore symbolism underlies the power of narratives to structure our understandings and decisions. There are five essential points here.

First, the causal power of social structures (Elder-Vass 2010) arises from our symbolic capacities (Deacon 1998). These structures impact on our brains in many ways (Berger 1963, Berger and Luckmann 1966), and we influence these structures – another aspect of our being open systems, but now involving symbolic aspects – which certainly have causal powers. If society has passed a law about when you can cross the street, you are constrained to wait at a red traffic light and cross when it is green – with minute-by-minute symbolic information changing your brain state and hence your actions. More complex is how the laws of chess shape movements of physical pieces on a chess board via a learning process leading to those rules being embodied in the details of neural networks in our brains.

Second, this interaction enables transforming technologies to occur. This introduces a quite new effect; the ability to completely transform the future over long timescales by invention of new technologies which change possibilities in a transformative way (Arthur 2009), being carefully designed

to do so (Dieter and Schmidt 2021). Future technology is completely impossible to predict: it depends on creative insights concerning how causal effects can be combined in completely new ways (Cropley 2015). There is an element of randomness in how this comes about which we do not understand – how a flash of insight comes to us, which can then be developed into a technological breakthrough. But we do know there is a great deal of randomness in brain operations at both the cellular and molecular level (Mitchell 2018) that must somehow underlie openness for such insights.

Third, new transforming ideas spread rapidly through nations across the world, so although there are certainly local customs and worldviews, there is an underlying openness of mental boundaries whereby ideas such as radios, cell phones, CAT scanners, GPS systems and so on spread world-wide on very short timescales and thereafter change life forever – for better or worse. Nations – and the minds in them – are in this way open systems. Transport by trains, motor cars, ships, and aircraft extends this openness to physical artefacts and people so that nations are no longer isolated – leading to the huge complex of social problems as to when immigrants are welcomed and when they are kept out. The whole issue of open system becomes a key topic at the social, economic, and political levels of society.

Fourth, this means that we are open systems in the time dimension as well: cultural and technological discoveries change future possibilities on timescales that transcend those of individuals, families, and dynasties. We can read a book that changes our minds on the basis of what happened hundreds or thousands of years ago: time travel occurs from the minds of Plato, Aristotle, Shakespeare, Charles Dickens, and so on affecting us today at a time $\mathbf{t_1}$ after we have read the book, which we had not done at time $\mathbf{t_0 < t_1}$.

Fifth, overall this results in the transforming power of stories (Gottschall 2012) and narratives (Johnson *et al* 2020) which are a key way the mind understands complex situations and makes decisions. As individuals or groups, we are open to the influence of narratives that transform our understanding of the situation, and hence our actions. News and social media are a key part of the equation that completely transcends the physical levels at the bottom, but certainly change physical outcomes. The ecology of ideas and narratives of any specific society is an open system.

**7: The cosmological context: an open system over time?**

Our cosmological context – the expanding and evolving universe that leads to the existence of galaxies, stars, and planets (Peebles 2020) - enables the existence of life. This is of course based in the underlying physics (Strassler 2024). Much has been written on why the universe and this physics is of such a nature that life can exist, but I will not pursue that here (Ellis 2014). The issue I now turn to is, does Laplacian determinism return if we consider the universe as a whole, when all the

influences impacting on local open systems are themselves determined uniquely by the initial data for the universe itself? Does that data together with the laws that govern the universe uniquely determine everything that happens? Or should the universe be regarded as an open system over time, with outcomes occurring allowed by but not necessitated by that data?

I will not engage in an extensive detailed argument in this regard: for that see Ellis (2021). I will just make three comments that I believe are conclusive.

Firstly, quantum theory only predicts probable outcomes, not specific ones. That is the core of its nature (Isham 2001, Zagoskin 2015, Baggott 2016). Initial data in the early universe – say at the Last Scattering Surface – therefore does not determine unique outcomes at later times. Contextual wavefunction collapse takes place and results in the specific outcomes that occur with probabilities according to Bohr's rule (Drossel and Ellis 2018). Quantum chemistry (Karplus 2014) is the key link between physics and biological outcomes – a form of probabilistic contextual wavefunction collapse.

Secondly, fluctuations at the molecular level in living systems wipe out any memory of previous states at this level on extremely short timescales (Graham 2023). Biology makes use of this molecular chaos to extract order at higher levels from disorder at lower levels via molecular machines (Hoffmann 2012, Noble 2021, Noble and Noble 2021, Ball 2023). The fact that we are evolved open systems with agency enables us to steer our own fate to a greater or lesser degree, depending on our family, social, economic, and intellectual history (Mitchell 2023). Physics *per se* is only one of the factors determining outcomes. Causal closure only takes place when all interacting elements and levels at different timescales are taken into account (Ellis 2020). Human agency involving progressive discovery of social and technological options (Arthur 2009) and economic and political decisions determine what happens .at human scales. History shapes outcomes.

Third, the knock-down argument is this. Current outcomes such as the design of iPhones and Jumbo jet aircraft, all of Shakespeare's sonnets, Einstein's theory of General Relativity, intelligent argumentation about open systems (as in this book), the corruption of the Supreme Court of the United States, could not possibly be a unique outcome of plausible physical processes taking place in the early universe. These lead to modulated Gaussian fluctuations on the Last Scattering Surface through well understood astrophysical processes (Peter and Uzan 2017, Peebles 2020). These fluctuations cannot be encoded versions of all those later outcomes, which *inter alia* contain logical arguments such as in this book and detailed designs for digital computers (Harris and Harris 2013). Study astrophysics and cosmology as long as you like, and you will find no trace of any astrophysical process that can possibly lead to such intelligent logical outcomes.

However a referee comments *"I was not convinced by the last `knock-down argument'. …. The claim `Study astrophysics and cosmology as long as you like, and you will find no trace of any astrophysical process that can possibly lead to such intelligent logical outcomes' will appear to be overly rash for skeptical readers."* My response is that I believe in physics, not magic. The processes described by Peebles (2020) cannot of themselves produce logical outcomes such as the design of a digital computer – there is no hint whatever in Peeble's book of any physical process that could possibly lead to such an outcome. So the supposed "skeptical reader" has to be a believer in some kind of Intelligent Design process, whereby the physical outcomes of standard cosmology (modulated random Gaussian fluctuations on the Last Scattering Surface) are overwritten by some kind of Demiurge who understands the fundamentals of digital computer design. He/she/it also composes sonnets, writes sonatas, selects tactics that took place during the Battle of Waterloo, composed the referee's comments, and so on.

By contrast, in my view the plausible origin of such intelligent outcomes is that the cosmos creates conditions whereby planets, life, ecosystems, and then intelligent beings come into existence by evolutionary and developmental processes on different timescales. Human beings are then, through their agency (Mitchell 2023), able to pursue literature, arts, and science (Ginsburg and Jablonka 2019). Through them new things come into existence that cannot be anticipated on the basis of the detailed initial state of the early universe – because they are not uniquely specified by that state. The physical universe is therefore open in time.

**Acknowledgments**

I thank two referees for helpful comments

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**Chapte**r for *Open Systems: Physics, Metaphysics, and Methodology* (2025: Oxford University Press) **edited by** Stephan Hartmann S.Hartmann@lmu.de and Michael Cuffaro mike@michaelcuffaro.com

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