Informational Unification of Intelligent Life with Fundamental Physics[*]

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(Dated: March 3, 2017)

The appearance of informational ideas across the natural sciences is highly suggestive. This essay argues that the conceptual dichotomy between fundamental physics and the emergence of intelligent life will be reconciled in a framework underpinned by physical information. Case studies from foundational physics to non-equilibrium thermodynamics and the origin of biology to consciousness draw from recent advances in the literature. By systematically synthesising the rich phenomenological roles of information, we pinpoint a series of informational phase transitions that engendered life and high-level cognition. Natural language emerged as an additional channel of information transfer on top of genetics, allowing agents to plan from ancestral experience unencumbered by neural memory or lifespan.

I. INTRODUCTION

A great divergence exists in the natural sciences. Fundamental physics enjoys spectacularly principled and predictive success. The recent direct observations of the Higgs boson [1, 2] and gravitational waves [3] are among the most exquisite experimental tests of the Standard Model and General Relativity. Meanwhile, pressing questions for how intelligent life physically arises remain stubbornly far from such levels of theoretical predictivity or empirical precision. Life exhibits aims and agency, notions absent from their microscopic laws. Given physics and biology study facets of the same world, how can this dichotomy be reconciled?

Advances across many fields already suggest that information underpins a wide spectrum of natural phenomena. Fundamentally, the physical properties of information are furnished by relativity and quantum mechanics [4–6], while black holes and spacetime see tantalising yet perplexing theoretical links with information and thermodynamics [7–10]. Indeed, thermodynamic connections with information are widely studied, more recently in quantum regimes and experiments [11, 12]. Entropy maximisation far from equilibrium has been related to the hierarchical structures in biology [13, 14] and emergence of intelligent behaviour [15, 16]. Meanwhile, the challenge of defining life is revealing thermodynamic and informational insights into the origin of life [17–21]. The culminating mystery is how cognitive sentience emerges from a neural network, with further hints that informational complexity could illuminate neurobiology [22], consciousness [23], intelligence [24, 25] and linguistics [26, 27]. Statistical physics even extends to understanding collective social dynamics [28].

While much of this progress is disconnected and nascent, the ubiquity of information is highly suggestive. Thus, we elevate physical information to the focus of fundamental physics through to intelligent life, and examine its rich conceptual and phenomenological roles that any reconciling theoretical framework must contain. Importantly, this synthesis provides such unifying efforts with concrete, theory-independent ingredients and objectives. This essay is structured as follows. Section II discusses issues surrounding the dichotomy. Section III presents the phenomenological aspects of informational unification. Section IV summarises our conclusions.

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[*] Submitted to the *FQXi Essay Contest 2016–17: 'Wandering Towards a Goal'*

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II. DISSECTING THE DICHOTOMY

The central dichotomy of the natural sciences addressed in this essay is:

> *Why are the fundamental laws of physics formulated without reference to goal-oriented intelligent behaviour or conscious agency, whereas living and complex systems in nature that emerge from them are?*

To proceed, we must disambiguate what goals and intelligence are to assess where they are or not present, which reveals issues underlying this conflict of scientific worldviews. Subtleties in defining life and consciousness are deferred to Section III. Thus we briefly examine the following:

- What is a goal?
- What is intelligence?
- How did the dichotomy arise?

What is a goal? The pursuit of goals is intuitively used to distinguish life from non-life [17, 18]. At its simplest, a parameter is extremised. *E. coli* bacteria minimise their distance to glucose while an oak seedling maximises its photosynthesis rate. Indeed entropy maximisation, which has a statistical origin, is linked with biology [13, 14, 19]. But how necessary is life for goal oriented behaviour? After all, abiotic machines can win the ancient game of Go [25]. Equally, why do we not make this interpretation with fundamental particles? Alluding to Wheeler's *It from Bit* mantra [4], one might argue an electron is aware of the potential it traverses (perceived how?), with a goal of following (why?) the spacetime trajectory that extremises its action (calculated how?). One suggests that electrons exhibit purposeful behaviour. Though such an interpretation exists, it really illustrates a pitfall in quantifying goals too simply and broadly as parameter extremisation. Summoning Occam's razor, there is no physical basis for any perception, computation or choice that necessitates predicting electron kinematics with notions of goals.

What is intelligence? It is better to embed goals into a measure of intelligence, but our human intuition often contaminates its definition. The classic Turing test relies on machines responding with human verisimilitude, or recent interpretations of mechanical simulations cite the human 'cognitive niche' [15]. In 2007, Legg and Hutter formally quantified intelligence independent of human psychology. Synthesising a plethora of literature and assuming a toy agent–environment framework, the duo proposed an influential definition of intelligence [24]; the informal version[1] reads:

> *Intelligence measures an agent's ability to achieve goals in a wide range of environments.*

The agent is the intelligent entity in question, and the environment is everything else. The quantitative definition contains complementary measures of (a) simplicity and (b) complexity in achieving goals. Namely, one aspect measures an agent's choice of the simplest means to achieve its goal (Occam's razor). The complexity measures the degree to which the agent can respond to a 'wide range' of environments. The perception and decision making processes require information transfer, storage and synthesis in view of achieving goals. Intelligent life has machinery for information processing—DNA and the neural network of the brain. DNA has the ability for replication, transcription, mutation and feedback with the environment, while complex neural systems augment agency with adaptive learning and active cognitive processes.

How did the dichotomy arise? Before proceeding, let us acknowledge a philosophical issue. As Anderson penned, *More is different* [29]: collective dynamics may be computationally unfeasible from first principles, but organising abstractions yield predictivity. We are all made of electrons and protons, but biologists work with cells and organisms. Similarly, cultural consensus or political factions are more useful concepts for understanding social dynamics than studying thoughts of individuals [28]. But to what extent do these emergent structures have the same reality as their building blocks? Or, are they mere simplifying constructs of the scientist hoping to make empirical progress? From everyday experience, humans and butterflies are certainly more tangible than their quark dynamics, but to what extent social classes or market forces. When we speak of goals or agency, these could be abstractions to explain biological behaviour as their physical origin is so difficult to pin down [18, 23, 24]. Resolving these ontological problems is beyond the scope of this work.

III. INFORMATIONAL UNIFICATION

A. The fundamental physics of information and life

We approach the dichotomy as a question of the natural sciences. Given the role of information in each field remains nascently understood, it is too early to propose unifying theoretical principles. We instead address the more timely, scientifically profitable and important challenge:

> *What are the theory-independent observable phenomena and informational links behind the origin of life and intelligence that a unifying framework must contain?*

Historically, this phenomenological agenda opened crucial windows into the underlying theory, such as organising chemical elements by empirical properties into the Periodic Table before quantum mechanics, and this scheme underpins our arguments.

The physicality of information. Fundamental physics is intimately tied with information, and shapes the structures for its propagation in life and the universe. But first, we ask *what is information?* Definitions of information and its close kin, distinguishability, are sufficiently subtle that they are often circular, one of the issues Constructor Theory aims to resolve [30] (but we will not delve into it). Practically, information has two hallmarks: 1) *substrate independence*—we regard information without referring to its medium of instantiation; 2) *interoperability*—we move information across media and its properties are unchanged. These traits seem universal, whether we speak of magnetic tape or genetic material. But, its (computational) limitations differ vastly between classical and quantum regimes [6, 12]. Quantum mechanics is one of the pillars of fundamental physics, and distinguishability is at its core. Good quantum numbers are the only labels that allow two states to be distinguished and encode information, say the spin up or down of electrons. Entropy quantifies our lack of information about a system's underlying probability distribution[2]. Removing the distinguishability of states and forgetting information is limited by Landauer's principle. It states that erasing 1 bit of information necessarily dissipates $k_B \ln 2$ of energy, where k_B is Boltzmann's constant, thus evidencing its physicality [11].

The inseparability of spacetime and information. Relativity also sees deep connections with information. Lorentz symmetry of spacetime bounds information transfer to the speed of light. Experimentally, even non-local correlations of quantum entanglement cannot manifest superluminal communication [5]. Information theory may even facilitate the herculean feat of consistently unifying gravity with quantum theory. There are hints that classical spacetime geometry emerges from the entanglement entropy of states in quantum gravity [8]. Moreover, rich thermodynamic structure has been revealed in the theory of black holes beyond a simple area scaling law of entropy [9], but the purported loss of information associated with their radiation remains unresolved [10]. Whatever microscopic phenomena are responsible for the macroscopic causal structure of spacetime, information cannot influence a distant pocket of the universe outside its light cone. A critical corollary of this limitation is the primordial cosmic acceleration needed to reconcile locality of information with the order 10^{-5} fluctuations observed in the cosmic microwave background [31] that seed structure formation.

Forces for life. Interactions are needed for information: an immutable object cannot carry the latter (and has no observable sense or arrow of time). Further, measurement acquires information via interactions, so this interplay is inextricable from science itself. The fundamental forces ultimately govern information propagation, but also endow the physical structures for information storage such as DNA. Only two interactions in nature are long-range: gravitation and electromagnetism. Long-range forces propagate information far in space and time. They thus engender macroscopic structures, be it astrophysical or biological. Gravity ensured an expanding universe yet material locally collapsed into galactic and stellar clusters, while its weakness permits nearly unimpeded information transfer via gravitational radiation [3]. The strength of electromagnetism sets the size of atoms and drives dissipation in galaxy formation, while ensuring hydrogen bonds are sufficiently strong to hold the helical structure of DNA, yet weak enough to allow replication. Just two forces underlie these diverse structures, but perhaps more profound is that no other long-range forces can exist in our universe, due to field theoretic consistency arguments by Weinberg [32]. Meanwhile, the two nuclear forces are confined to microscopic ranges, but their effects are nonetheless crucial for life. They drive stellar fusion that manufactures heavy elements such as phosphorus required to construct DNA, while enabling our Sun to power the energetic machinery on Earth. That fundamental parameters appear fine-tuned for life to exist has long been discussed [33], an issue only exacerbated by the parametric tuning of the observed Higgs boson mass [1, 2] and cosmological vacuum energy [34]. Anthropic considerations[3] are outside the scope of this essay.

Scale-dependent hierarchy of information. In quantum field theories governing the fundamental forces, scale dependence is an inevitability of interactions. For scale-dependent theories of nature, renormalisation ensures only a small number of terms in the action are important to describe the dynamics at low energies, constrained by any symmetry in the system[4]. Information is lost about the high energy (small length scales) with the many possible 'irrelevant operators' in the action becoming negligible at low energy regimes (large length scales). Renormalisation generates a hierarchy of scales with different phases of information. Crucially, different microscopic theories can give the same low energy macroscopic physics—the concept of universality. Many ultraviolet completions of gravity are possible, but must ultimately reproduce the Standard Model formulated with only a few 'relevant operators' in the action, and General Relativity is viewed as an effective field theory [35]. Wilsonian renormalisation considers theories to be effective up to an energy cutoff. Meanwhile, biochemical enzymes proceed without needing information about the dynamics of quarks and gluons. The effective theory has new, emergent degrees of freedom, which may be of completely different character in its dynamics and information content to the microcosm. Renormalisation is why *More is different* [29] and why macroscopic phenomena, such as life, can be so qualitatively distinct from its underlying laws.

B. Inevitability of order, complexity and life

Fundamental physics enabled the favorable cosmic conditions for life. But answering *how did life arise?* is only well-posed once the equally vexing question *what is life?* is well-defined. A definition of life is not only key to understanding Earth-bound biology, but ever more relevant in extraterrestrial searches given the prevalence of observed exoplanets [36]. Considering life's geochemical origin, rather than the 'primordial soup' picture in the popular mind, life likely began in an environment of highly dynamical bio-energetic non-equilibrium, such as submarine hydrothermal vents up to 4.28 billion years ago, geologically soon after Earth's formation [20]. Analysis of primitive organisms suggests that harnessing adenosine triphosphate—the 'currency' of cellular metabolism—likely exploited geochemical gradients by such vents, when a dearth of atmospheric oxygen prevailed [21]. But an immediate question is how can such ordered structures appear when entropy increases towards thermal equilibrium? In this vain, Schrödinger notably introduced the somewhat dubious concept of 'negative entropy' associated with life [37].

Emergence of low entropy complexity. Surprisingly, maximising entropy production in systems far from equilibrium can actually engender the spontaneous emergence of low-entropy structures such as biology [13–15, 17, 19]. The second law of thermodynamics favours information of ordered systems to be lost over time due to thermal fluctuations and dissipation. But such random processes are slow. In the early universe, stresses grew as gravity induced collapse of light elements in slight over-densities from primordial quantum fluctuations. These were relaxed by the formation of low entropy structures such as stars and galaxies, reaching mechanical equilibrium. Non-equilibrium processes funneled into smaller scales. The existence of liquid water allows gradients and stresses to be induced by solar energy or electric charge gradients within thunderclouds. Tropical cyclones are ordered and complex structures that develop to relieve such atmospheric thermal stresses, transporting and dissipating free energy via powerful convective processes [13]. But even pure thermal processes have their limitations. As Kleidon argues, life emerges because of its ability to bypass limitations of purely abiotic processes, maximising the global entropy at the highest rate [14]. Whether storms or life, sustaining low entropy structures in the face of the second law, oxidation and other dissipative forces, requires intrinsic non-equilibrium to be maintained. This leads to the emergence of elaborate processes in life, such as woodlands regulating their local hydrological and solar climate such that it does not suffer large temperature fluctuations of inhospitable locales as deserts.

The need for such regulatory mechanisms to maintain low entropy states is manifested in the sheer complexity of living organisms. Even the most primitive lifeforms exhibit sophisticated biochemical machinery [21], while the human body have complex transport networks to deliver hormones or immune response, in addition to homeostasis for regulating their bodies at 37°C. Though such complexity necessary for survival developed through natural selection, Goldenfeld and Woese identify several shortcomings in the *Modern Synthesis* (of Darwinian evolution and Mendelian inheritance), suggesting revision to this paradigm is needed [17]. It is claimed that the key sign of complexity is the loss of causality: nonlinear feedback, strong fluctuations, hierarchy of spatio-temporal scales all characterise complexity [17]. With this, it is important to keep in mind that even intrinsically deterministic laws need not remain predictive, as evident in chaotic dynamics[5], both classical [38] and even quantum regimes [39]. Perhaps the most sophisticated process of self-sustainability is replication, which has been linked with the production of entropy [19].

Life as the first phase transition of information. Self-replication alone is however insufficient to define life, given crystals have periodic structures that can be replicated. Walker and Davies distinguish between 'trivial' and 'non-trivial' self-replication [18]. The former are like crystals, whereby the 'algorithmic' (instructional) information governing the construction of another unit is negligible compared to that in the entire system—crystals implicitly rely only on the physics of the environment. Life handles far more complex information, but in a qualitatively different way. As Walker and Davies propose [18]:

> *Life begins as a phase transition when information gains top-down causal efficacy over the matter that instantiates it.*

There is a physical decoupling of the information from the structure it is encoded on. The function of DNA has two roles akin to the hardware–software duality. The software is the genetic information encoding algorithmic instructions (as opposed to a blueprint) for replication of the system. The hardware is the substrate where the information is encoded and can itself be physically copied. A separate context-aware 'supervisory' unit is then required to decide which task is performed. The surrounding system can exert causal influence over the genome itself, realising what is dubbed top-down causation [40].

This is a transition to bi-directional causal influence of the information. Indeed, biological systems are inherently self-referential [17], namely the rules underlying the response of an organism to its environment are encoded in the genome, while environmental selection shapes this genome over time[6]. In contrast, states never alter the mathematical form of dynamical laws in fundamental physics. The equations of quantum electrodynamics are functions of electron position governing its trajectory, but those equations never change themselves, whether it is produced in the Large Hadron Collider or meeting its energetic demise in the particle detector. The physical mechanism underlying this transition remains unclear[7], but its identification makes this task well-posed.

C. Consciousness, language and high intelligence

Accounting for the emergence of life may be subtle, but its diversity is remarkable. What stands out are that decisions made in brains of cats and humans have unambiguous qualitative differences to those in algae and trees. Neural processes typically arise on time scales of order 100 ms and there is consensus that quantum effects decohere too quickly for any relevance [41]. Thus, the brain is almost certainly not a quantum computer and in principle can be modelled as a classical neural network. The information processing of neurons is subject to thermodynamic constraints [22]. But we would like to address how the cognitive agency that arises in humans is so distinct from other known lifeforms.

Consciousness as the second phase transition of information. Studying consciousness has ramifications not only in clinical medicine for vegetative patients, but also artificial intelligence. Artificial neural networks can now win games of Go [25], well outside the agency of newborn or sleepwalking humans. In biological systems, neural correlates of consciousness in the brain can be mapped thanks to advances in medical imaging. But how can we quantify the relative consciousness of these different states? Numerical interconnectedness can lead to richer experiences, but equally, little consciousness is associated with the cerebellum, which houses 80% of the 86 billion nerve cells in the brain [23]. Tononi and Koch review the current state of neurobiological research, highlighting the Integrated Information Theory for consciousness [23]. The essence of this framework quantifies the information generated by a network as a whole due to the causal architecture of the tightly interacting sub-elements. Consciousness occurs as complex network information associated with an experience is integrated and cannot be reduced to its parts. Importantly, the framework makes clinical and laboratory predictions. It accounts for different degrees of consciousness from vegetative states to fully awake humans, while also ascribing consciousness to simple animals. They further argue social aggregates—be it two people or millions—are not conscious as the collective entity has reduced informational complexity than an individual, while (eventual) artificial simulations of consciousness will not be conscious, given they do not exert physical causal efficacy [23].

A reversal of environmental constraint on agents. When combined with intelligence, conscious agents make decisions and achieve goals with greater complexity and efficacy. Once thought to be unique to human cognition, tool use is seen in bumblebees adapting to new environmental pressures to move miniature balls into laboratory targets for rewards [42], or even emerge in mechanical simulations that maximise causal entropy [15]. But, humans have the power to manipulate their environment to their advantage in truly exceptional ways above other lifeforms: mitigating undesirable effects such as infectious diseases or cold weather via medicine or lighting fires. There is now strong evidence we are in a distinct Anthropocene epoch [43], where human activity has altered the geological, ecological and climatic processes on Earth. The effects of humanity's purposeful ability certainly sits with maximising entropy production à la Kleidon [14], but why is it absent in other lifeforms? We argue this reversal of influence against natural selection, whereby agents gain causal efficacy over its environment using complex information synthesis, is a distinct phase of intelligence.

This phenomenon is more than a smooth increase of intelligence, even as viewed in the Legg–Hunter framework [24]. It is a further phase transition in the role of information, akin to the Walker–Davies transition in life [18], but now to a distinct phase of 'high intelligence' distinguished by metacognition—the awareness of our own cognitive state and the wider environment. This state endows the ability to systematically study the laws of nature for exploitation of the environment far from the agent's immediate temporal or perceivable spatial scale, be it cosmic or subatomic. This is one of the hallmarks of humanity. How these abilities, together with artistic creativity and introspective morality, emerge from evolutionary processes is unclear. Pinning down their origin is a formidable challenge for evolutionary biology, neuropsychology, and artificial intelligence. We argue that these remarkable high level abstractions is a natural phenomenon governed by another informational phase transition that engenders natural language. As with the origin of life [18], the physical mechanism that drove this remains elusive.

Language as the third phase transition of information. Natural language is widely regarded to be the distinguishing feature that separates human intelligence from the rest of biology [26, 27, 44]. It enables propagation of complex semantic information encoded in simple building blocks, obeying syntactic rules, with sufficient redundancy for error mitigation. Anthropological aspects of language bear parallels with genetic evolution [26]. Indeed, analysis of information entropy of distinct languages reveals universal traits, hinting at a common linguistic ancestor [27], while even the learning process may have thermodynamic connections [16]. The Walker–Davies informational framework for genetics [18] has analogies in language, which also exhibits decoupling of information from substrate and bi-directional causality. The information content of words is largely independent of whether it is spoken, read on a computer screen. The environment equally shapes the language, just as a language can influence the perception of the environment. A notable example is a study conducted with stone-age tribes and English speakers, which yielded evidence that our perception of colour depends on language [45].

Within the Legg–Hunter framework of intelligence [24], language provides a powerful means of information storage, synthesis and propagation for an agent to achieve goals. It can process information about the environment with a scope and efficiency far outstripping genetics alone. Human language has almost certainly facilitated, even enabled, metacognition. Synthesizing perceptions allows not only agents to make decisions to achieve their next goal, but for their offspring to achieve the same goals much more efficiently. Baby humans born now or a millennium ago are both equally technologically illiterate. Yet through language, the children of today need not embark on the centuries of technological enlightenment their ancestors required to use a computer. Where the memory limitations of the brain are reached, written language provides a comparatively limitless storage. Abstract ideas containing rich information can be succinctly captured in monosyllabic words such as 'joy' or 'sad'. Indeed, words of human languages have on average the order of a few bits per word [27]. Language coarse grains and imparts new systems of thought to synthesize information in an agent's environment. In Kleidon's picture [14], language is a low-entropy structure, that ultimately facilitates the increase in the rate of global entropy production of its user. With natural language, agents can learn new behaviours and exert influence on the environment with far greater complexity, even manually revising genetics itself.

IV. CONCLUSION

This essay approached the dichotomy between fundamental physics and intelligent life as a question in the natural sciences. We tackled the more timely task of conceptually synthesising otherwise disconnected lines of recent advances into a holistic informational account. Information appears from the outset at the heart of relativity and quantum theory, with the resulting fundamental forces shaping the cosmic conditions for life. Information plays distinct roles at each hierarchy of scales governed by effective field theories. Information complexity is central to how biology and consciousness arise. In such contexts, thermodynamic and entropic information remain operationally distinct from their genetic and linguistic counterparts, with information undergoing a series of phase transitions. Life and metacognition emerge as new informational phases, enabling intelligent species to accelerate entropy production beyond abiotic processes, in ways of greater complexity than, and without reference to, the underlying dynamics.

Our analysis of the diverse phenomenological roles of information importantly provides conceptual benchmarks for what a unifying theoretical framework must contain or predict, and merits a more detailed formal treatment. In addition to being empirically testable, such a theory hopes to address what information physically is, why it appears so universal, how the transitions identified arise, and its relation to the scientific method, which continue to elude consensus. Even if this theory turns out not to be informational, this work evidences that it very likely reduces to this picture in some limit. Historically, unification of distinct phenomena opened deep insights into nature and sweeping technological advances, be it electricity with magnetism or molecular chemistry with inheritance. One speculates that we are witnessing the start of a profound informational unification in the natural sciences.

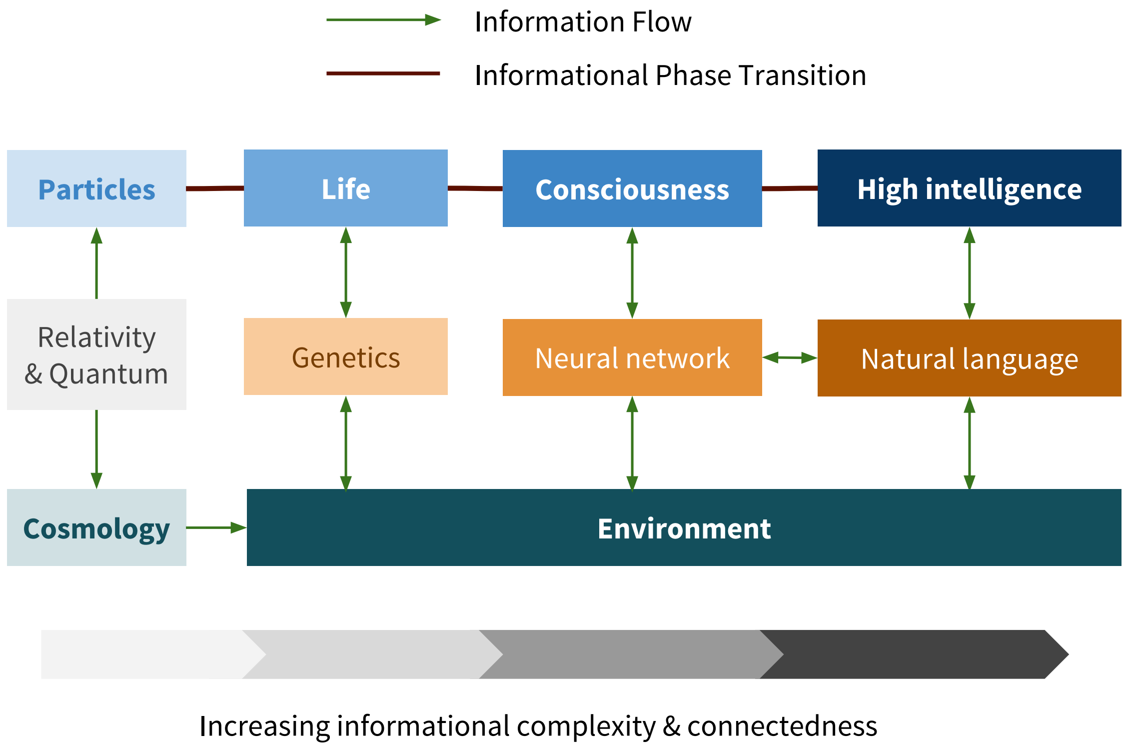

FIG. 1. Schematic summary of informational phases (upper blue), manifestations of information (middle orange) and the environment (lower green) of increasing complexity and connectedness (darkness).

Acknowledgements

JL thanks the STFC and University of Oxford for support. SM is supported by CIRS and University of Sussex. We extend our gratitude to the Perimeter Institute and PSI programme for giving us the opportunity to meet and form this collaboration.

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ENDNOTES

[1] The motivation of Legg and Hutter was to overcome various shortcomings of existing measures of machine intelligence. The formal mathematical definition proposed for the *universal intelligence* Υ of agent π is:

$$\Upsilon(\pi) := \sum_{\mu \in \mathcal{E}} 2^{-K(\mu)} V_\mu^\pi . \tag{1}$$

Here, $\mathcal{E}$ is the space of all computable reward summable environmental measures in reference to machine $\mathcal{U}$. The weight 2^{-K} measures the complexity of the environment μ, where K is the Kolmogorov complexity function. The value function V_μ^π quantifies the agent's 'ability to achieve'. For further details of the formalism and discussion, see Ref. [24].

[2] In quantum systems, the probability distribution is generalised to the density matrix, allowing qualitatively different constraints on information processing [6, 12].

[3] Motivated by the ubiquitous appearance of fine-tuned fundamental parameters and the 'string landscape' of vacua, some have speculated the existence of a cosmological multiverse. The values of the electroweak vacuum expectation value or cosmological constant assume a spectrum of values, where the universe we inhabit consists of those that are suitable for intelligent life to emerge.

[4] These few terms have so-called 'relevant couplings'. In renomalisation group flows, these are the couplings that do not become negligible in the infrared, as they are not suppressed by $\sim 1/\Lambda$, where Λ is the cut-off energy scale. Scale independent theories have even greater constraints due to conformal invariance. Indentifying these can be subtle. Classically, the SU(3) gauge field theory is conformal, but there is an anomaly in the quantum theory, thus quantum chromodynamics is scale-dependent. A well studied example in theoretical physics of a conformal quantum field theory is the maximally supersymmetric $\mathcal{N} = 4$ Yang-Mills theory.

[5] In classically deterministic dynamical systems as simple as double pendula or the full Navier–Stokes evolution of an atmospheric fluid, the resulting phase space trajectories can be highly sensitive to the initial conditions. The apparent fine-tuning and loss of predictivity is not due to intrinsic complexity, but finite experimental and computational precision.

[6] To cast this more formally, the self-referential dynamical rules R map an initial state S_i to a final state S_f are themselves state-dependent i.e. $R(S_i) = R_1$, while $R(S_f) = R_2$, where the dynamical rules themselves differ $R_1 \neq R_2$. On the other hand, laws that are not state-dependent retain the same mathematical structure during dynamical evolution $R_1 = R_2$.

[7] Indeed, how order parameters, the first or second order nature, critical exponents, or the statistical physics of phase transitions formalism apply to such complex living systems far from equilibrium is unclear, but such informational transitions are qualitatively suggestive.