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Complexity Theory in Biology and Technology: Broken Symmetries and Emergence

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Abstract: This paper discusses *complexity theory*, that is, the many theories that have been proposed for emergence of complexity from the underlying physics. Our aim is to identify which aspects have turned out to be the more fundamental ones as regards the emergence of biology, engineering, and digital computing, as opposed to those that are in fact more peripheral in these contexts. In the cases we consider, complexity arises via adaptive modular hierarchical structures that are open systems involving broken symmetries. Each emergent level is causally effective because of the meshing together of upwards and downwards causation that takes place consistently with the underlying physics. Various physical constraints limit the outcomes that can be achieved. The underlying issue concerns the origin of consciousness and agency given the basis of life in physics, which is structured starting from symmetries and variational principles with no trace of agency. A possible solution is to admit that consciousness is an irreducible emergent property of matter.

Keywords: complexity theory; emergence; biology; technology; agency; symmetries

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1. On Complexity in Contemporary Science

This section discusses the question at issue (Section 1.1), research methodology (Section 1.2), and a historical perspective (Section 1.3).

1.1. The Question at Issue

"Complexity Theory" is a name that has been given to a variety of results in recent decades, covering many areas of mathematics, physics, and biology, where surprising results occur because of the non-linear nature of the reactions taking place. However, it is not clear without further investigation which of these results are in fact of importance in mainstream biology and technology. This paper aims to clarify that question.

1.2. Research Methodology

The method used was to carry out a literature survey of the various relevant approaches to 'complexity theory', and evaluate their relevance in relation to what has turned out nowadays to be the core of the emergence of biology and technology.

1.3. A Historical Perspective

Over the years, many proposals have been made as to what the core of complexity is [1–3], although there is considerable scepticism about some of the claims made [4]. There has also been a somewhat distinct literature on the nature of emergence, which is of a more philosophical nature [5–9]. We are primarily concerned here with the former rather than the latter, although they are not independent.

The term complexity is increasingly frequent, not only in scientific language, but also in socio-economic, medical, and even political terms. The origin of that usage can be identified in the increasingly widespread belief that the world has reached a level of interrelationship between its various components that makes it less and less predictable and controllable. In recent decades, the world of science has shifted a significant part of its attention and resources towards the study of complex systems, i.e., systems characterized by substantial difficulty in treating them on the basis of simple cause–effect relationships, with complexity emerging from the interrelation between subsystems endowed with some simple or articulated internal structure. A particular structure generally considered complex is the human brain, which manifests this nature from many points of view, from biophysical ones such as action potential spike chains to those concerning cognition and perception, the formation of thought, and agency.

One line of thought holds that the essential nature of complex systems can be captured by a single basic set of concepts and associated dynamics models, unifying them within the same conceptual architecture. By highlighting common features of substantially different problems, as early as the end of the 1970s, people were reflecting on how to deal in a unified way with problems deriving from physics, chemistry, biology, computer science, psychology, linguistics, sociology, and economics. Particularly studied are complex adaptive systems [10,11] , which include living beings.

The laws regulating collective behaviour can differ greatly from those that regulate the behaviour of individual elements, dealing with the spontaneous emergence of variety and organization, starting from a large numbers of elementary components of a few kinds that interact easily with each other [12]. There seems to be consensus in defining complex systems as those whose behaviour cannot be directly determined by the analysis of their constituent elements, and the scale of observation influences the degree of complexity that can be encountered. The complex emerges when the whole is not simply reducible to the sum of the parts [13]. The need to tackle problems such as meteorology, the properties of non-linear or disordered systems, and the organization of living matter, has increasingly shifted the attention of science towards the study of this type of system [14]. Few concepts appeared in recent decades have proved so penetrating as that of complexity, to the point of asking whether complexity provides a new scientific paradigm, in the Kuhnian sense of the term, reflected in the award of the Nobel Prize to Giorgio Parisi [15].

Important scientific results have been obtained such as the field of computational complexity, the theory of spin glasses, the dynamics of chaotic systems, and neuronal networks. This anti-reductionist trend culminated in an epistemological movement, including the complexity theory of Morin [16] and Prigogine [17]. Any macroscopic description involves a loss of information, relating to knowing the multitude of details of the microscopic level; thanks to this loss of information, systems that are very different systems from each other in detail have the same global behaviour. This is the phenomenon of multiple realizability [18,19]. In the transition from micro to macro, the loss of information causes countless microscopically different systems to have the same macroscopic behaviour. This raises the issue of determining a clear boundary between irrelevant details and essential information [20,21] as, for example, in the debate on "junk DNA" in genetics.

However there is a problem. Not all that has been labelled as "Complexity Science" has in fact been of major significance in the emergence of the truly complex systems we see around us: specifically, life, technology, digital computers, and social systems. *Wikipedia* states it thus in its entry on *Complexity Economics*:

> *In a series of publications, Scientific American journalist John Horgan ridiculed the movement as being the fourth C among the "failed fads" of "complexity, chaos, catastrophe, and cybernetics". In 1997, Horgan wrote that the approach had "created some potent metaphors: the butterfly effect, fractals, artificial life, the edge of chaos, self-organized criticality. But they have not told us anything about the world that is both concrete and truly surprising, either in a negative or in a positive sense".*

In the following, we will consider the wide range of approaches that have been taken to understanding complexity, and then comment on what role we see them as playing when we compare them with each other. There are three domains we will consider:

- Biology;
- Technology;
- Complexity science;

aiming to show clearly how the latter relates to the first two, which we will show have many common features. We will not deal with psychology and sociology or social structures and institutions in the present paper, even though they are certainly highly complex and share many common features with what we present; they bring in too many extra issues.

The paper considers the puzzle of complexity, the variety of approaches (Section 2), the role each approach plays when viewed today (Section 3), the cognitive limits of materialism, the irreducibility of life and consciousness (Section 4); and a conclusion (Section 5). We will give links to Wikipedia articles where useful, as they are often convenient accessible summaries of complex material. All these articles were accessed in September 2023.

2. The Puzzle of Complexity: The Variety of Approaches

We consider here, in turn, biology (Section 2.1), technology (Section 2.2), and complexity science (Section 2.3). We shall see that the same basic principles underlie the first two domains, and are rather different than those emphasized in the third.

2.1. Biology

As regards biology, the understanding of its complexity developed over centuries, starting already with Hippocrates and Aristotle, and proceeding to understanding of physiology, developmental biology, and evolution.

2.1.1. Hierarchy

Biology is of a hierarchical nature, based at the bottom in the same material stuff as all other matter we see around us.

Upwards and downwards causation takes place as indicated [22,23]. The key influences from above **L13** are incoming solar radiation, which in combination with a dark night acting as a heat sink sky enables the biosphere to function in energy terms, and the gravitational fields of the Sun and Moon, causing tides. All this is based in the possibilities physics allows at each emergent level [24].

2.1.2. Physiology

The first real studies of complexity were studies of physiology. Circulation of blood by the heart was already discussed by many including Hippocrates (c.460-370 BC), but was first put on a solid footing by William Harvey in 1628.

Physiological systems: One by one all the physiological systems of human beings were understood: 1. the respiratory system, 2. digestive system /excretory system, 3. circulatory system /cardiovascular/vascular system, 4. urinary system/renal/urinary tract, 5. integumentary system, 6. skeletal system, 7. muscular system, 8. endocrine system, 9. lymphatic system, 10. nervous system, and 11. reproductive system, working together in harmony to provide our physical being. Each of the physiological systems is in turn of a hierarchical nature related to its function, as in the hierarchical nature of the heart [25].

Cells: A crucial discovery by Hooke in 1665 was the way all life is based in microscopic cells , with their complex substructures (cytoplasm, nucleus, ribosomes, mitochondria, etc.) being elucidated in following years. This is the first level at which all the functions of life occur. There are many more than 13 different cell types in the human body.

Molecular biology: In 1953, James Watson and Francis Crick published the double helical structure of DNA. The first protein structures to be solved were myoglobin by John Kendrew in 1958 and haemoglobin by Max Perutz in 1963. This lead to the understandings of supramolecular chemistry [26,27] regarding how supramolecular conformational change underlies molecular biology. In particular, the molecular structure of the nucleic acids RNA and DNA [28] and of many proteins [29] have been determined, and hence the molecular biology of the cell elucidated [30].

Vast numbers: Life emerges out of vast numbers of atoms and molecules and cells:

- The number of cells in the human body is 10^{13};
- The number of proteins in a cell is 4×10^7;
- The number of proteins in a human body is 4×10^{20};
- The number of atoms in a typical cell is 10^{14};
- The number of atoms in a human being is 10^{27}.

None of this is obvious, because both atoms and cells are so small (which is why it took so long for both the cellular structure of life and atomic structure of matter to be proved).

Stochasticity and molecular machines: Molecules in air at normal room temperature are moving at between 300 to 400 metres per second. A biomolecule collides 10^{13} times a second with water molecules. Biology has evolved to use the opportunities at the bottom [31] to thrive on molecular stochasticity, so molecular machines reliably extract order from this chaos [32,33]. Examples are how motor proteins (myosin, kinesin, dynein) are responsible for muscle contraction and move cargo inside cells, DNA polymerases replicate DNA, RNA polymerases produce mRNA, the spliceosome removes introns, and the ribosome synthesises proteins.

Three key principles occur, all involving contextual logical branching:

1. Form and function in biology are related by a multi-scale [34] hierarchical structure, forming an integrated whole [35,36] with structure/function relations occurring at all emergent scales [37,38], involving variables relevant to that level [39].
2. Metabolism involves (a). enzyme-catalyzed reactions converting energy in food to forms suitable for cellular processes, (b). conversion of matter in food to building blocks for biomolecules, and (c). the elimination of metabolic wastes [40]. These reactions are crucial in allowing growth and reproduction, maintenance of structure, and environmental responses, and take place in the form of metabolic networks [41].
3. Homeostasis in biology was discovered in 1865 by Claude Bernard [42] and then rediscovered in an engineering context by Norbert Wiener in 1961 [43] as a concept he named *Cybernetics*. The common core of both processes is feedback control loops that counteract deviations from a chosen goal state by corrective action, thus acting top-down to control micro-states so that desired macro states emerge (as in a thermostat) and so enabling contextual dynamical branching (e.g., a heater element is on or off). It is a principle of very wide application in biology, with the set points determined by evolution, and engineering and society, with chosen setpoints.

2.1.3. Reproduction and Developmental Processes

The existence of individual organisms occurs via developmental processes based at the cellular level in cell division followed by cell differentiation.

Cell division is part of a cell cycle during which the cell grows and replicates its chromosomes before dividing. It should be noted that this process itself is not coded in DNA but rather is built into the inherited cell structure, duplicated when cells divide and developmental systems are reproduced [44]. The process includes duplication of the gene itself in a complex process mediated by various RNAs, and followed by a careful proof reading and correction process whereby DNA replication errors are reduced by many orders of magnitude [45]. Also gene organelles divide by highly complex processes, as e.g., in the case of mitochondria.

Cell differentiation The same genetic information is encoded in the DNA in the chromosomes in every cell. Genes are segments of DNA that can be read to produce proteins, with regulatory sequences controlling transcription of the gene. Which genes are read is determined by binding factors that turn genes on so that they are transcribed into messenger RNA (mRNA) molecules, which in turn are translated into proteins [28]. The issue is which specific genes are read in which cells in which position in the developing embryo at what time [46,47]. This is controlled by gene regulatory networks on the basis of positional information that controls cell fate decision [48–51]. The resultant proteins then determine what kind of cell emerges at each position [52,53] and so determines embryo and hence adult organism structure.

2.1.4. Darwin and Adaptive Selection

So where does the DNA that shapes biological outcomes come from? As is well known, by processes of variation and selection as proposed by Charles Darwin in 1868 [54], now commonly agreed to on as a key feature of biology [55] explaining apparent design by natural processes [56]; organisms are thereby adapted to their environment [57].

Of course, when Darwin developed the theory, it was a theory of macroscopic variation (Levels **L9** and upwards in Table 1), for the concept of a gene was not even known at that point. It has since been recast as a theory of genetic evolution, and many writings represent it as only being such. This ignores the undoubted role of physiology in the process of evolutionary selection [58] (e.g., as in the case of Darwin's finches), thereby undermining the central achievement of evolutionary theory [59].

Table 1. The hierarchy of structure for biology on Earth. Levels **L0** to **L4** are strictly physical, and their nature is unaffected by biology. Level **L5** is the first distinctly biological level, and level L6 the first level where all the processes of life occur. Higher levels are the Earth (the planet as a whole), Sun (essential to life), Solar System, Galaxy, and so on. The bottom level **L0** is unknown (it could be strings, but they are not well defined). The up arrows indicate upward emergence from a specific configuration; the down arrows indicate downward determination of specific outcomes in particular contexts.

L13		Biosphere	
L12	⇑	Ecosystems	⇓
L11	⇑	Populations	⇓
L10	⇑	Organisms	⇓
L9	⇑	Physiological Systems	⇓
L8	⇑	Tissues	⇓
L7	⇑	Cells	⇓
L6	⇑	Cytoplasm, organelles	⇓
L5	⇑	Macromolecules	⇓
L4	⇑	Molecules	⇓
L3	⇑	Atoms	⇓
L2	⇑	Protons Neutrons Electrons	⇓
L1	⇑	Quarks Leptons Bosons Higgs	⇓
L0		Unknown physics (if it exists)	

In fact, evolutionary adaptation takes place simultaneously at all the emergent levels L4 to L12 in Table 1 in an integrated way [23], as has to be the case, because of the way the levels interact with each other (see, e.g., [60] for the interaction of physiology, proteins, and genes). Neither organisms nor genes are levels uniquely determining evolutionary outcomes. In particular, selection takes place of developmental systems [61], so there is a strong "Evo-Devo" interaction between evolutionary and developmental processes [52,53]

From a broader viewpoint, evolution is an example of the power of *Complex Adaptive Systems* [11], a theme we return to later.

2.1.5. Networks

Given these vast numbers, interactions often take the form of networks, where simple interactions are combined to give complex outcomes. Their nature is characterised by graph theory, and one can study the statistics of networks, such as existence of hubs and the degree to which they are scale-free, etc. [62,63]. One can also determine what network motifs occur [64], with specific functions. Biological networks are of two types:

- **Interaction networks** with specific functions, particularly metabolic networks [41,65], gene regulatory networks [66], and cell signalling networks [67]. These occur inside compartments bounded by membranes that keep the interactants from drifting away, so spatial location is a key aspect of their functioning [68]. They reliably produce macro level functions out of the huge number of interactions of specific components at the micro level. One can model their function by Boolean interaction networks, thus distinguishing biological from random networks [69].
- **Nervous systems** are structural networks [70] which are themselves hierarchically organised [71]. They consist of neurons (cells made of dendrites, a nucleus, and axons) connected by synapses to other neurons, together forming a physical neural network [72]. Action potential spike chains travelling down axons to other neurons convey information and allow adaptive resonant networks to occur. The hierarchical structure of the brain [71] allows hierarchical dynamics to occur [73].

Note that it is not sufficient to give statistics of the roughly 10^{14} synaptic connections of the roughly 10^{11} neurons in a human brain to characterise it. It is the specific details of these connections that embodies our unique memories and abilities that make each of us the human individuals that we are.

2.1.6. Perception, Learning, Prediction, and Agency

The extraordinary thing that occurs is the emergence of qualia and mental processes out of physical entities, namely action potential spike chains propagating in the physical brain. Indeed, there are a variety of emergent properties arising:

- **Learning:** Plasticity at macro and micro scales enables learning on the basis of experience [74]. The brain is altered by our experiences and understandings, and able to recall (or at least reconstruct) associated memories;
- **Perception** is enabled by predictive processing of incoming data [75], enabled by cortico-thalamic circuits and experienced as qualia;
- **Planning:** internal models of the world based on past experience and present data allows prediction of outcomes, and so values-based choices between action options and consequent actions [76];
- **Randomness:** stochastic dynamics is a principle of brain function [77]. Indeed, stochasticity at the micro-level underlies the capacity for higher level processes to select optimal lower level outcomes on the basis of higher level needs [78,79], allowing higher levels to break free of the iron determinism of physics per se;
- **Agency and free will:** This amounts to the emergence of agency [80–82], and, indeed, effective free will emerges [76,83].

2.1.7. The Emergent Whole

What emerges in biology are open systems [84] that are consequently dissipative systems [85] for thermodynamic reasons, which form an integrated whole [86], where each part works together to enable the whole to function. All the characteristics of life emerge, including function at every level [38], and agency.

Measures: We do not attempt to give a measure of their complexity, out of all the measures proposed [87], as the numbers of particles and molecules and cells and neural connections involved are too large. One needs some measure characterising the extraordinary properties remarked on in Section 2.1.6. Perhaps those are the dimensions that should be used as a basis for such a measure.

2.2. Technology

Another area where true complexity exists is technology, which also has a modular hierarchical nature [88] for reasons explained in [89,90] (see Section 3.1.3). Each technology is based in some phenomenon captured and put to use ([88]:51,53).There is a fundamental similarity between some technologies: mechanical, hydraulic, and electrical circuits have completely analogous dynamics as expressed in their equations of motion [91,92].

2.2.1. Basics

Taking electronic systems as an example, electronic circuits are made of active and passive components that are combined to give complex outcomes.

- Wires channel the electron flows that comprise currents; batteries or generators drive the current; lights or heaters or motors act as output devices of the circuit; and switches enable control by turning the current on or off;
- Capacitors C, coils L, resistors R, and diodes are the basic elements allowing electric circuits to perform functions such as being an amplifier, radio receiver, or oscillator ;
- Contextual logical branching is enabled by two-way switches, sensors, and input signals, controlling relays, vacuum tubes, or transistors linked to create logic gates.

2.2.2. Digital Computers and Computation

The core phenomenon underlying current technologies is computation, as technology of all kinds is largely controlled by algorithms realised in computer programs.

Digital computer systems have orthogonal hierarchies enabling their functioning: a physical hierarchy [93] supporting a hierarchical logical structure ([22]: Section 2)encoded in computer programs processed by a hierarchy of virtual machines [93]. Black boxing takes place [94] as a part of the abstraction that is key to modular structuring [90].

Integrated circuits [95] allow Very Large Scale Integration (VLSI) so that billions of transistors are included on a single chip. Thus as in the case of biology discussed above, the number of components is vast: these are networks of great complexity. This allows structuring of microprocessors which process information in a computational cycle with a clock generating pulses which synchronize the operations of its components.

Computation outcomes are determined by the program loaded and data processed, whether that was provided at the start, or is input in an ongoing way from external data sources such as sensors. The core feature is Turing's insight [96] that digital representation is possible of any information whatsoever, including the program for manipulating the data.

2.2.3. Digital Computers and Effective Agency

Abstract causation: Because algorithms are abstract concepts, as are virtual machines, abstract causation is taking place when a digital computer runs a program realising an algorithm. This is discussed illuminatingly by Dasgupta [97], who comments that both physical and abstract causation take place during a computational process, with liminal causation (neither purely physical nor purely abstract) linking the two.

Effective agency: The resulting systems are capable of effective agency in the sense of choosing appropriate outcomes on the basis of ongoing incoming data, and acting so as to achieve these outcomes. A key example here is aircraft autopilots, including automatic landing systems that receive data on a second by second basis from radio and radar systems and can on that basis control the aircraft to a safe landing even in dense fog, without intervention by the pilots.

2.2.4. Randomness and Openness

Randomness: In contrast with the biological case, where randomness at the micro level is rife and is exploited by microbiological processes, in this case, such randomness is minimal: processes are more or less entirely deterministic, with exceptions caused by cosmic rays, electromagnetic noise, or power-supply fluctuations. Thus, when it is operating on given initial data, it is basically a deterministic system, with outcomes uniquely determined by the program loaded and data then processed.

The internet: However, this is not how it works in practice. Because effectively all digital computers are now connected to the internet, they are themselves open systems continually receiving information from that wider context and, in turn, sending messages and information to it. Thus, in the end as in the case of biology, you cannot predict future outcomes from a full knowledge of the state of the computer itself at any one time: it is affected by unpredictable incoming data (much of which is hidden from the user).

2.2.5. The Emergent Whole

Again what emerges is a complex whole where upwards and downwards causation occurs in both the physical and logical hierarchies ([22]: Section 2, [98]) enabled by compilers or interpreters and allowing virtual machines to function at each emergent abstract level. Effective agency emerges, to the extent that current debates about Artificial Intelligence ("AI") are seriously considering if it is able to be a serious threat to humanity. In any event Chatbots such as ChatGPT can carry out tasks such as writing and debugging computer programs, translate and summarize texts, and so on. Thus it approaches human capabilities.

2.3. Complexity Science

We now turn to various facets of "complexity science" [1,2] that have been identified as such since the 1950s. Many fascinating aspects of how complex outcomes can emerge from the underlying physics have been uncovered. The Wikipedia article on Complex Systems states,

> "*Complex systems are systems whose behaviour is intrinsically difficult to model due to the dependencies, competitions, relationships, or other types of interactions between their parts or between a given system and its environment. Systems that are"complex" have distinct properties that arise from these relationships, such as nonlinearity, emergence, spontaneous order, adaptation, and feedback loops, among others. Because such systems appear in a wide variety of fields, the commonalities among them have become the topic of their independent area of research. In many cases, it is useful to represent such a system as a network where the nodes represent the components and links to their interactions.*"

We now look in turn at seven major themes considered in this literature.

2.3.1. Information Theory and Algorithmic Complexity

Information Theory (Claude Shannon, 1948 [99]) studies the measurement of amount of information stored and transmitted, and characterises important limits on such usage. This has led to *Algorithmic Complexity Theory* [2] as attempts to measure complexity. However none of this has anything to do with the meaning of that information. Thus it does not directly relate to the way that the *content* of information is crucial in both biology [100,101] and in technology via its use in computer systems [88,97].

2.3.2. Reaction–Diffusion Equations

The reaction diffusion equation and related particle differential equations can lead to surprisingly complex patterns arising from simple initial data. This was pointed out by Alan Turing in 1952 [102], and plays a significant role in pattern formation during the initial stages of developmental processes in biology, as he pointed out, for example, in determining zebra stripes, giraffe mottling, and butterfly wing patterns.

2.3.3. General Systems Theory and Complex Adaptive Systems

General systems theory was developed by Kenneth Boulding (1956) [103], Stafford Beer (1966) [104], and Ludwig von Bertalanffy (1968) [105] as an attempt at a general theory of how complex systems work. It proved by and large to be too generic to lead to specific outcomes, although it touched on many important ideas. Its most important outcome are arguably firstly, recognising the importance of cybernetics [43,106] in biology and engineering, and generalising it to Jay Forrester's systems dynamics, which is a form of predictive feedback control. Secondly, introducing the general idea of Complex Adaptive Systems, which is a key concept in complexity theory.

2.3.4. Catastrophe Theory

Catastrophe theory, proposed by Renee Thom in 1977 [107,108], is the first of the forms of complexity classified by Manson [2] as "Deterministic complexity". It shows how bifurcations in behaviour of physical or social systems can occur only in a small number of geometrically characterised ways (fold, cusp, swallowtail, and butterfly catastrophes in the case of one active variable), deterministically resulting in sudden transitions from an unstable state to a more stable state. It is important in topics such as gravitational lensing, but use in the case of truly complex systems such as human self-pity and the stock market has been criticised. In these contexts it is descriptive rather than predictive.

2.3.5. Chaotic Dynamical Systems, Strange Attractors, and Self-Organised Criticality

This is the second of the forms of complexity classified by Manson [2] as "Deterministic complexity". Constraints can turn generic dynamical behaviour into that characterised as dynamical systems [109]. In particular situations, this can result in existence of *chaotic dynamical systems* [110,111] where arbitrarily small differences in initial conditions can lead to very different outcomes in a deterministic but unpredictable way—the "Butterfly effect" created by strange attractors, with bifurcation cascades taking place. An extraordinary emergent effect is the nature of fractals, such as the Mandelbrot set.

An interesting discovery is that in some cases, self-organization and order emerge at the edge of chaos, thus self-organised criticality takes place [112], with the system in effect tuning itself as it evolves towards criticality. Self-organized criticality is a property of dynamical systems that have a critical point as an attractor. These studies often refer to behaviour of cellular automata.

2.3.6. Scaling of Complexity

Studies by Ludwig Von Bertalanffy [113] and Geoffrey West [114,115] show how emergent properties in many contexts are associated with a variety of scaling laws that restrict what is possible. This is an important aspect of emergent complexity.

2.3.7. Some Further Cases

Here are some further cases that have been classified under "complexity theory":

1. Cellular automata, developed particularly by Wolfram (1984, 2002) [116,117], have been much studied. In some cases self-organization and order emerge at the edge of chaos, or self-organised criticality takes place. John Conway's "Game of Life " (see Gardner (1970)) is probably the most famous cellular automaton.
2. Spin glasses [118], which show cooperative behavior in terms of the freezing of spin directions when below a 'freezing temperature'.
3. Flocking of birds [119] leading to murmurations where each bird keeps track of seven neighbouring birds is a bottom-up dynamic similar to the Game of Life.
4. Slime moulds coordinate their activities by communicating with each other through traveling waves of the molecule cAMP [120] which enables them to have some properties similar to those of animal neural systems. Arguably there is downward coordination taking place in this case.

These are, indeed, interesting examples of complex behaviour, but do not play a central role in mainstream biology and technology.

3. The Role Each Approach Plays When Viewed Today

We consider here the core of complex emergence in biology and technology, including digital computer systems (Section 3.1), the periphery (Section 3.2).

3.1. The Core

We propose that the following are the core features allowing complexity involving coordination of billions of components so as to attain emergent functions, as in the case of life and digital computer systems, to emerge.

3.1.1. The Centre

- Non-linearity. The dynamics involved, and their emergent outcomes, are manifestly non-linear. While the basic elements making up a complex system may indeed have linear dynamics, they are assembled in highly non-linear ways [121], for example involving interacting hierarchical feedback control circuits and interaction networks;
- Organisation. These elements are systematically organised so as to achieve desired emergent outcomes [122,123]. This occurs either via the processes of natural selection in the case of biology [57,59], or by processes of design and manufacture [89], as in the case of digital computers [97], aircraft, and so on;
- Open systems. These are all open systems with well defined boundaries [84], so unpredictable incoming influences influence their dynamics [124]. They can, however, be structured so as to attained desired goals, despite this fact;
- Dissipative structures and metabolism. In terms of their interaction with the environment, they can be characterised as dissipative structures [85], extracting their order at a thermodynamic cost to the environment via metabolic processes that extract material and energy from the environment, transform them to usable form, utilise them for functional purposes, and dispose of waste products and heat;
- Use of information to shape outcomes. All life inherits information, collects it by various sensory systems, analyses it and stores it, and uses it to determine desirable outcomes [100,101]. Modern technology is centrally based in information collection, storage, and analysis via digital computers so as to make optimal choices [88,97].

3.1.2. Symmetry, Broken Symmetry, and Topology

From a physics viewpoint, what underlies emergence, in addition to coarse graining, is one of three features:

- Symmetry, such as gauge groups that characterise the basic physics itself, and in many cases symmetries characterising emergent structures [125], for example crystal symmetries leading to Bloch's Theorem and related emergent properties.
- Broken symmetries. More complex emergence is based in broken symmetries, as pointed out by Anderson [39]. This is key *inter alia* to biological emergence through the immense complexity of macromolecular shape [26,27], and to technological emergence through the structure of transistors [98].
- Topological effects [126–128], which by nature are non-local: you cannot determine topology from local quantities without determining how they fit together at emergent scales. This occurs particularly in the case of topological insulators, feedback control loops, and physical and interaction networks.

3.1.3. Modular Hierarchical Structures, Multiple Realisability

Biological and technological systems are modular hierarchical structures for very good reasons, as explained by Herbert Simon [89]. The basic principle is to break up a complex task into simple operations, design modules to carry out the simple operations, and then combine the outcomes to produce the desired result. This involves abstraction, labelling, information hiding, and multiple realisability, as explained clearly by Booch et al. [90]

- The modules are more tightly bound relative to the inter-module interactions, where being "tightly bound" is characterised by the associated binding energy (see, e.g., [129]), and generically have more rapid dynamical processes than those between modules;
- The modular structure comes into being by developmental processes (biology) or manufacturing (technology), and possibly by self-organisation in the right context where all the components in a contained space have the necessary nature;
- Upwards effects in the emergent structure take place by contextual coarse-graining or black boxing, depending on context;
- Downwards effects occur via interlevel time-dependent constraints on the one hand, and by higher levels creating, modifying, or deleting lower level elements on the other;

- Through these effects, new properties occur at every emergent level that were not present at lower levels. They are characterised by effective theories at each level [38,130] in terms of emergent variables appropriate to that level [39];
- Multiple realisability takes place whereby higher level functions or adaptations can be realised by many different configurations at lower levels [19,131]. This means that effective laws characterising functions at higher levels, such as homeostasis or natural selection in biology or a computation in a digital computer, cannot be described in any simple way at relevant lower levels (genes, molecules, electrons) because at that level they are characterised by billions of possible alternatives.

3.1.4. Function and Adaptation

The key difference between physics per se and both and biology and technology is that the latter centrally embody function and purpose at every emergent level in the hierarchy (Table 1) above the physical levels **L0–L4** [132–135].

In order that they can successfully do so, they must:

- Continually adapt to the environment in which they operate so that they can meet the challenges it represents, thus they must be *Complex Adaptive Systems* [3,10,11];
- This occurs through evolutionary processes, whereby characteristics of a class of entities are determined by adaptive processes, as in the case of Darwinian evolution in biology [54,59] and in technological evolution [88]. In each case, branching dynamics takes place via selection of best outcomes from a set of alternatives;
- This adaptation takes place consistently at every emergent level simultaneously; it has to do so in order that system functionality is maintained all the time [23];
- It also occurs through developmental processes [50,86], whereby individual entities come into being and then continually adapt to the environment on an ongoing basis.

3.1.5. Stability via Feedback Control

They must be stable under the kinds of perturbations they are likely to meet on an ongoing basis, and so must be *homeostatic systems* [36,136] (in the case of biology, the setpoints being determined through evolutionary processes) or *cybernetic systems* [43,106] (where the setpoints are either set by design, or are adjustable on an ongoing basis). Branching dynamics occurs via contextual use of information [100,101].

3.1.6. Causal Closure and Stochasticity

Because of the meshing together of upwards and downwards causation, causal closure involves the whole set of interacting levels [137,138]; any smaller set of levels will contain dynamic variables whose evolution is undefined. Because of this, every level of the emergent hierarchy (Table 1) adapts to context simultaneously during both evolutionary and developmental processes.

It is crucial that the vast numbers of components involved in a cell at the micro level are moving at high velocities and colliding millions of times a second, so molecular stochasticity is a key feature of biological dynamics at those levels [32,139]. Because of this, stochasticity provides freedom whereby lower levels can be adapted to higher level needs, thereby enabling the possibility of agency [78,79]. Lower level outcomes can be selected as needed from the myriad of options that occur every microsecond.

3.1.7. Interaction Networks

Networks are a key feature whereby simple interactions can combine to produce complex results. In biology they include:

- Metabolic networks [41,60,65];
- Gene regulatory networks [60,66];
- Their interactions with each other [140];
- Neural networks [70,141].

These have come to be what they are through natural selection. In the case of technology, they include

- VLSI circuit boards with billions of components
- Artificial Neural Networks of many kinds, including networks underlying Artificial Intelligence and programs such as ChatGPT-4.
- The global Internet

the first two having arisen via very careful processes of design, and the third by a rather haphazard developmental process.

3.1.8. Emergent Agency

Agency occurs in all higher forms of life, characterised as any living thing with eyes, ears, feet, or wings (it may well occur in other simpler organisms, but we claim that in these cases it is indisputable: these are all organs associated with agency, so they are evidence it exists in these cases). According to Philip Ball [142],

> "*The whole point about agency is that it can be versatile, adaptive and improvisational. Agency evolves precisely because living organisms are liable to encounter challenges that evolution itself is too slow to adapt to*".

That is why it has evolved [143,144]. Ball continues,

> "*What most distinguishes agents is that they have reasons for actions, which in turn elicit value judgements: a primitive notion of meaning*" [142]

It involves predictive processing of possible outcomes via contextual use of information, enabling obtaining desired out comes as contexts change. Agency also occurs also in high level technological systems, such as automatic pilots in aircraft, self-driving cars, and automated factories, which make contextual choices as to what to do next.

Characteristics of agency are stated by Potter and Mitchell [145] as shown in Table 2, where we have for convenience renumbered these items.

Table 2. The elements of agency: a comparison of [145] and this paper.

	Potter and Mitchell [145]	***This Paper***
1	Thermodynamic autonomy	Metabolism
2	Persistence	Homeostasis
3	Holistic integration,	Hierarchy
4	Multiple realisability	Multiple realisability
5	Low-level indeterminacy	Low-level indeterminacy
6	Historicity	Memory
7	Endogenous activity	Endogenous activity
8	Agent-level normativity	Value judgements

These are, essentially, the characteristics we have emphasized above for both living systems and technology. There is a close correspondence between them, highlighting the properties needed for agency to emerge.

Number 7 is what makes it agency, the others are what are required for it to occur. There are different levels of endogenous activity in that cybernetic systems will attain set goals $\mathbf{G}$ reliably, but a higher level of goal-seeking occurs if the goals $\mathbf{G}$ in a cybernetic system are themselves selected in an adaptive way according to some selection criteria C_1, and a yet higher level if the selection criteria C_1 themselves are selected according to even higher selection criteria C_2 [146].

Number 8 emphasizes that agency is always connected with function associated with some purpose (see [98] for the case of digital computers). Low-level indeterminacy, emphasized above in §3.1.5 in the case of biology, occurs also in all technological systems because of the Shot Noise that arises because of the discrete nature of the charges carried by electrons or holes. Reliable outcomes emerge in the technological case because of thresholds associated with coarse graining.

3.2. The Periphery

It will be clear from the above that some topics listed under "Complexity Theory" (Section 2.3) do not occur in the core of biological and technological emergence as characterised in Section 3.1, apart from *cybernetics* and *complex adaptive systems*, which are characterised as important in both cases. That does not mean that the others are not important under certain circumstances, characterising very interesting complex behaviour that can indeed occur, but rather that they are not part of the core set of features that underlie existence of biological and technological complexity. Rather, sometimes they are additional features adding to and modulating that core theory in significant ways.

3.2.1. Reaction–Diffusion Equations

The Reaction–Diffusion equations studied by Turing [102] and others play an important role during early embryonic development, when diffusion of active agents sets up basic patterns such as occur in zebra strips and butterfly wings [147]. Thus, they crucially provide the initial context for developmental processes to take place. However, they do not characterise how that development itself takes place.

3.2.2. Catastrophe Theory, Basins of Attraction, and Critical Transitions

The geometrically characterised kinds of transformations of properties described by Catastrophe Theory [107,108] are not widely used in biology or technology nowadays. A different characterisations of when dynamical outcomes in these contexts change from one kind of behaviour to another is when dynamical systems change from one basin of attraction to another [148]. Such critical transitions are associated with symmetry breaking [149]. A key case where this occurs is in the changes between possible outcomes that occur in Waddington's epigenetic landscapes [150]. Amongst the most important events where this occurs are the major evolutionary transitions in biology [151] and technology [88].

3.2.3. Chaotic Dynamical Systems, Strange Attractors, and Fractals

Chaotic dynamical systems are not of significance for emergent complexity in biology and technology *per se*, but rather because they can affect the context within which these operate. Indeed in in biology and technology, with a possible exception of some brain dynamics [152], these systems are structured precisely so that chaotic dynamical systems (in the technical sense) and strange attractors do not arise. Thus the edge of chaos [112] does not lead to emergence in these contexts. It is a metaphor rather than a tight relation: it reflects the fact that if the dynamics is too deterministically based in initial data alone, agency is not possible, whereas if stochastic dynamics at the molecular level is considered, there is openness for agency to occur [78,79]. But stochastic dynamics is quite different than a chaotic dynamic system.

However chaotic dynamics in the technical sense arises in systems that are the context for biology and engineering, and specifically as regards weather, where the unpredictability of the Real Butterfly Effect occurs [153]. This causes unpredictability in biology as people and animals respond to unpredictable rain and wind, as well as in some technological contexts, such as aircraft automatic landing systems.

As to fractals, biology is not self similar at different scales, that is the whole point of the hierarchy shown in Table 1 where structure is quite different at different scales. However self-similarity occurs to a limited degree in a few contexts in biology, such as the lungs; but even then this involves self-similarity for only a few recurrences, not the endless repetition of self-similarity involved in fractals such as the Mandelbrot set.

3.2.4. Limiting Relations: Speeds, Size, Scaling, and Geometry

Various physical effects limit what emergent outcomes are possible in modular hierarchical structures, and hence in complex systems. Examples are diffusion rates for ions and molecules at synapses. There are also limits on transmission of information as characterised by Shannon's Information Theory [99], however it is not clear that they play a significant role in the brain, for example in limiting propagation of information by action potential spike chains. However this is important in technology via coding theory.

These physical limits result in the scaling relations for complexity studied by Von Bertalanffy [113] and West [114,115]. However, those relations assume the context provided by the core features discussed in §3.1. Another example of such limitations is that the geometry of the brain puts constraints on human brain function [154].

3.2.5. Measures of Complexity

We have not considered measures of complexity, which are often related to various entropy measures, in turn related to Information Theory. These are discussed in [155]. Integrated Information Theory [156] is the most sophisticated measure of this kind, particularly because it is carefully structured to relate to modular hierarchical dynamics, but the issue is whether it works in practice because of the huge number of connections in the brain or a digital computer.

Ross Ashby studied the foundations of self-organizing systems in an important article [157] which, in effect, also looks at this but in a different way by asking what is meant by the word "organisation". One needs something like a measure of the number of functional capacities, and emergent entity has at different levels to get at what emergent complexity in biology and technology is about.

4. Cognitive Limits of Materialism and the Irreducibility of Life and Consciousness

In the first pioneering scientists, such as Francis Bacon, Galileo Galilei, Rene Descartes, Blaise Pascal, and Isaac Newton, we identify an original opening to a broader and more unitary vision of the global knowledge of reality than existed before.

Considering the understandings of modern physics, science has become aware of the distance existing between foundational physical theories and the reality they investigate, and the ordinary world around us, noting oddities, wonders, and counter-intuitive experiences far from the macroscopic experiences of daily life at the quantum level. On the other hand physics, despite all its progress and potential, does not seem to be able to date to explain some of the most humanly relevant natural phenomena, such as life and consciousness, with rigorous accuracy.

Reductionist naturalism believes it is possible to explain the entire universe, including ourselves, by reducing it to fundamental physical laws, explaining life and mind in terms of physico-chemical evolution. Hence, biology, and the emergence of life in the cosmos, would be reduced to the laws of physics and chemistry, as would psychology, resulting from the emergence of mind and consciousness, be attributable to biological evolution. In this way, it is represented the fundamental framework in which the program of reductionist science is placed, which despite still having many knots to untie, is considered to be the only scientifically valid and viable road. Any all-encompassing theory of reality which is derived starting from a few fundamental physical-mathematical laws collides, however, with the impossibility of answering the question of why such laws are given, a question that seems insurmountable, and has to be satisfied with the (non) answer that that is just how things are.

We seek a line of research that contrasts with

- Cartesian dualism (which would not allow any unitary synthesis between matter and spirit);
- Reductionist materialism (which would claim to reduce the mind to material principles);
- Explicit theism, which would introduce a transcendent agent to explain life and consciousness from outside nature;

- Subjectivist idealism, which would lead everything back to the spirit by considering matter as pure appearance;
- Panpsychism, with an attempt to develop a scientific theory of awareness already present at the quantum level, connected to an emergent psycho-physical hypothesis where the mental is closely connected to physical complexity; this could explain the development required for natural selection, although the mystery of this emergence would remain.

We do not advocate any of these approaches. We rather support non-reductive physicalism, as do Gilette (2002) [158], List and Menzies (2009) [159], O'Connor and Churchill (2010) [160], Bishop (2012) [161], and Menzies (2015) [162].

The physical laws of the universe, being not totally deterministic and depending on boundary and initial conditions, leave various openings for the possible outcomes of processes in the future and, among these, there would be some more probable for the formation of complex organisms than others. Final or teleological causality has been excluded from modern sciences, and is considered an imaginary cause due to ignorance of the real causes, i.e., the efficient ones. However, this physical and causal reductionism fails to give full reason to what happens in the world of life [163]. Biological sciences appear more and more clearly as irreducible to physical science as hitherto understood.

Quantum physics is based on abstract mathematical information; in describing material reality, it risks identifying matter with this abstract information [164]. Each systemic theory/idealization describing reality does not coincide with reality itself, but describes various aspects of reality, not fully capturing it. This is a fundamental epistemological thesis, valid for any scientific, philosophical, or theological theory.

Furthermore, physical science studies matter from an external perspective, wanting to observe the objects present in reality from a neutral position; therefore, it only describes the external nature of objects, the phenomenon observed from outside, and is manifested externally, but never accesses the internal reality. If we want to avoid dualisms in describing physical reality, our inner conscience, sensations of various kinds, and other inner experiences must be taken into account. It would therefore be necessary to develop a physical theory that also explains the presence of consciousness in the natural world. Among the investigated proposals, we have:

- *Materialism*: there is only matter, understood as what is studied by current physics; this leads to a conflicting position between science and religion;
- *Dualism*: there is matter on one side, studied by physics, and consciousness on the other; it is a pro-independence position between science and religion;
- *Holism*: the whole is greater than the sum of its parts [86], therefore the unity of an entity cannot be explained by studying the parts composing it, according to the reductionist approach. In the unity of the entity, a novelty irreducible to its constituents appears [165,166].

Holism in physics, in particular in relation to quantum physics, has highlighted interesting and debated questions, such as the non-separability as a consequence of the holism of physical properties [167], the mental experiment of "delayed choice" about the spatial and temporal holism of the quantum world [168], and the indivisible whole of quantum objects [169]. As mentioned above, we support non-reductive physicalism, as well as holism. The way this works out in terms of the hierarchy of emergence in Table 1 is:

- Physical emergence holds from levels **L1** to **L3**;
- Chemical emergence occurs at level **L4**;
- Biological emergence from level **L5** up, with the first level with all the functions of life being **L7**;
- Something completely new occurs at level **L10**, namely agency; in the case of humans: consciousness, self-consciousness, and the ability for meta-reflection and so morality and responsibility.

The classic separation between res cogitans and res extensa, and the consequent fixation on the res extensa is not sufficient to understand physical reality, at most to explain it, with the previously indicated limits. This is well known in the philosophical field as Dilthey's distinction [170,171] between natural and spiritual sciences, according to which the former explain reality, while the latter try to understand it [172,172]. We do not enter here into the metaphysical issues to do with why the Universe exists and why it has the nature it does, which underlies these questions [173,174].

Finally, a useful comment from Edward Feser: *"Since conscious experience provides the observational evidence on which physics rests, physics presupposes the reality of conscious experience. Hence, if conscious experience is left out of physics' mathematical representation of nature, then the epistemology of physics once again entails that there must be more to reality than is captured by that mathematical representation"*. Equally, physics presupposes the existence of sufficient free will to plan and carry out experiments. Without this, no physics is possible.

5. Results

This paper has compared the various aspects of "Complexity Theory" as commonly discussed with the way emergence of complexity takes place in biological and technological systems. Aspects of complex emergence that are of key importance in those contexts are that, on the one hand, they are complex adaptive systems, and on the other, they are homeostatic or cybernetic systems. However, "complexity theory" as usually stated misses out the key element of the existence of modular hierarchical structuring, with the emergence of effective theories at each level. Other aspects of complexity theory as usually understood play significant roles in shaping how these structures emerge or function in particular contexts, as discussed in Section 3.2; however, cellular automata do not play a significant role in such emergence.

The key feature of cases such as the flight of starlings and spin glasses is explained best in Philip Ball's review of the new book by Giorgio Parisi:

> "*Parisi explains why reporters who were scratching their heads about how to explain spin glasses were missing the point of his research. His work isn't about this system or that—a specific metal alloy, or the flocks of starlings in Rome that Parisi studied as a complex system in the 2000s. It's about the universality of phenomena, whereby systems of many interacting components that look utterly different—be they flocks of starlings, groups of particles or the magnetic atoms in spin glasses—can be described using the same mathematics. The fact that you can do so isn't because there is a loose analogy between these systems but because they are all, at root, the same (collective) thing*".

The same applies to the tightly coupled biological and technological systems we consider here: they share the same core structural and dynamical principles (Section 3.1).

In all cases, broken symmetries are there freeing the emergent dynamics from the underlying physics symmetries, as pointed out so long ago by Phil Anderson [39] and exemplified in [175].

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