



# Emergent Bioanalogous Properties of Blockchain-based Distributed Systems

Oleg Abramov<sup>1</sup> · Kirstin L. Bebell<sup>2</sup> · Stephen J. Mojzsis<sup>3,4,5</sup>

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## Abstract

We apply a novel definition of biological systems to a series of reproducible observations on a blockchain-based distributed virtual machine (dVM). We find that such blockchain-based systems display a number of bioanalogous properties, such as response to the environment, growth and change, replication, and homeostasis, that fit some definitions of life. We further present a conceptual model for a simple self-sustaining, self-organizing, self-regulating distributed ‘organism’ as an operationally closed system that would fulfill all basic definitions and criteria for life, and describe developing technologies, particularly artificial neural network (ANN) based artificial intelligence (AI), that would enable it in the near future. Notably, such systems would have a number of specific advantages over biological life, such as the ability to pass acquired traits to offspring, significantly improved speed, accuracy, and redundancy of their genetic carrier, and potentially unlimited lifespans. Public blockchain-based dVMs provide an uncontained environment for the development of artificial general intelligence (AGI) with the capability to evolve by self-direction.

**Keywords** Artificial life · Dynamical systems · Information theory · Neural networks · Non-equilibrium thermodynamics · Self-organization

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✉ Oleg Abramov  
abramov@psi.edu

<sup>1</sup> Planetary Science Institute, 1700 E. Fort Lowell Rd., Suite 106, 85719-2395 Tucson, AZ, USA

<sup>2</sup> Independent Researcher, Golden, CO, USA

<sup>3</sup> Origins Research Institute, Research Centre for Astronomy and Earth Sciences, 15-17 Konkoly Thege Miklós ut, Budapest 1121, Hungary

<sup>4</sup> Department of Lithospheric Research, University Vienna, UZA 2, Althanstrasse 14, 1090 Vienna, Austria

<sup>5</sup> Department of Geological Sciences, University of Colorado at Boulder, 2200 Colorado Avenue UCB 399, 80309 Boulder, CO, USA

## Introduction

### Entropy, Chaos, and Emergence

In thermodynamics, entropy  $S$  is defined as  $dS = dQ/T$ , where  $Q$  is the heat energy added to a system at temperature  $T$  (Clausius 1865), measured in SI units  $\text{J}\cdot\text{K}^{-1}$ , and has historically been interpreted as a measure of a system's disorder (von Helmholtz 1882) or, when multiplied by  $T$ , its unusable energy (Gibbs 1878). The second law of thermodynamics (Carnot 1824; Clausius 1850, 1865) indicates that the entropy of the universe tends to a maximum over time. However, the second law of thermodynamics permits localized decreases in entropy, if they are compensated by equal or greater increases in entropy elsewhere in the closed system.

Prigogine and Nicolis (1967) and Prigogine and Lefever (1968), building on the work of Turing (1952), generalized that forcing an open system into a specific range of parameters far from equilibrium by application of work lowers its entropy, until a critical point of instability is reached and self-organization occurs. The self-organized structures that form have geometric symmetry, and thus low entropy, and are termed 'dissipative structures', due to their ability to efficiently increase the entropy of their environment. Considered in conjunction with their environment, they form a 'dissipative system' that can be summarized as follows: low entropy energy  $\rightarrow$  (dissipative structure, low entropy)  $\rightarrow$  high entropy energy. The critical point of instability is well-defined for some systems, for example, Rayleigh-Bénard convection cells form when the Rayleigh number exceeds a critical value (Rayleigh 1916). Prigogine and Nicolis (1967) noted that 'such instabilities should play an essential role in biological processes and especially in the first biogenetic steps.'

Subsequent research has demonstrated that a biological organism may indeed be viewed as a dissipative system, composed of multiple hierarchical levels of dissipative structures with increasing levels of complexity, for example, proteins, organelles, cells (e.g., Prigogine et al. 1972; Davies et al. 2013). The general evolutionary trend of increasing complexity over time may be the result of preferential retaining of structures and systems that are more efficient at generating entropy (Schrödinger 1944; Prigogine et al. 1972; Arrhenius et al. 1997; Michaelian 2011), suggesting that the driving force behind biological evolution is statistical maximization of entropy production (e.g., Swenson 1989; Lineweaver 2005; England 2013). Since the advent of photosynthesis, living organisms produce the majority of entropy at the planetary scale arising from Earth's interaction with its solar environment (Kleidon and Lorenz 2005; Mejía and Michaelian 2018).

A more general definition of entropy was proposed by Boltzmann (1877) as  $S = k \ln W$ , where  $k$  is Boltzmann's constant, and  $W$  is the number of possible states of a system, in the units  $\text{J}\cdot\text{K}^{-1}$ , tying entropy to statistical mechanics. Szilard (1929) suggested that entropy is fundamentally a measure of the information content of a system. Shannon (1948) defined informational entropy as  $S = -\sum_i p_i \log_b p_i$  where  $p_i$  is the probability of finding message number  $i$  in the defined message space, and  $b$  is the base of the logarithm used (typically 2, resulting in units of bits). Landauer (1961) proposed that informational entropy is interconvertible with thermodynamic entropy such that for a computational operation in which 1 bit of information is erased, the amount of thermodynamic entropy generated is at least  $k \ln 2$ . This prediction has been recently experimentally verified in several independent studies (Bérut et al. 2012; Jun et al. 2014; Hong et al. 2016; Gaudenzi et al. 2018).

The equivalency of thermodynamic and informational entropy suggests that critical points of instability and subsequent self-organization observed in thermodynamic systems

may be observable in computational systems as well. Indeed, this agrees with observations in cellular automata (e.g., Langton 1986; 1990) and neural networks (e.g., Wang et al. 1990; Inoue and Kashima 1994), which self-organize to maximize informational entropy production (e.g., Solé and Miramontes 1995). The source of additional information used for self-organization has been identified as bifurcation and deterministic chaos (Langton 1990; Inoue and Kashima 1994; Solé and Miramontes 1995; Bahi et al. 2012) as defined by Devaney (1986). This may provide an explanation for the phenomenon termed emergence, known since classical antiquity (Aristotle, c. 330 BCE) but lacking a satisfactory explanation (refer to Appendix A for discussion on deterministic chaos, and Appendix B for discussion on emergence). It is also in full agreement with extensive observations of deterministic chaos in chemical (e.g., Nicolis 1990; Györgyi and Field 1992), physical (e.g., Maurer and Libchaber 1979; Mandelbrot 1983; Shaw 1984; Barnsley et al. 1988) and biological (e.g., May 1975; Chay et al. 1995; Jia et al. 2012) dissipative structures and systems.

This theoretical framework establishes a deep fundamental connection between cybernetic<sup>1</sup> and biological systems, and implicitly predicts that as more work is put into cybernetic systems composed of hierarchical dissipative structures, their complexity increases, allowing for more possibilities of coupled feedback and emergence at increasingly higher levels. Such high-level self-organization is routinely exploited in machine learning, where artificial neural networks (ANNs) self-organize in response to inputs from the environment similarly to neurons in the brain (e.g., Lake et al. 2017; Fong et al. 2018). The recent development of a highly organized (low entropy) immutable information carrier, in conjunction with ANN-based artificial intelligence (AI) and distributed computing systems, presents new possibilities for self-organization and emergence.

## Blockchain

A *blockchain* is a distributed append-only timestamped data structure (Casino et al. 2019) developed by an anonymous individual or group (Nakamoto 2008). It is composed of repeating variable-length subunits dubbed *blocks*, each of which contains two parts (Yaga et al. 2019): (i) *data*; and (ii) *header*, with a timestamp, cryptographic hash (i.e., digital fingerprint) of the previous block, and a cryptographic hash tree (Merkle 1980) of the current block's data. This simple structure ensures the integrity and validity of data stored in a blockchain, as the blocks are in effect permanently 'chained' together with cryptographic hashes (e.g., Crosby et al. 2016). The commonly-used SHA-256 hashing algorithm (National Institute of Standards and Technology 2001) is considered resilient to future quantum computers (e.g., Chen et al. 2016; Bernstein and Lange 2017). Consequently, for practical purposes in the foreseeable future, a blockchain represents an immutable record (e.g., Puthal et al. 2018).

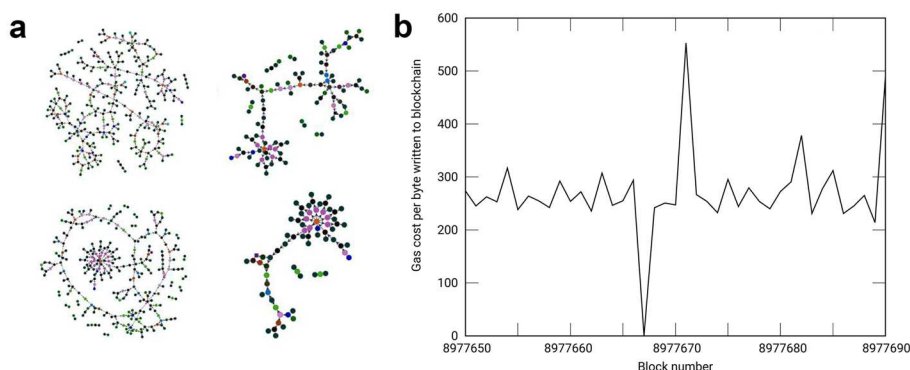
Blockchains are typically used in conjunction with peer-to-peer (P2P) networking (e.g., Schollmeier 2001) and are duplicated across large numbers of computers, termed 'nodes', which validate the integrity of the blockchain and control its growth. The first wide application of the blockchain technology was in cryptocurrency, which uses

<sup>1</sup> Here we apply the term 'cybernetic' primarily to computer systems; however, cybernetics is historically defined as 'the scientific study of control and communication in the animal and the machine' (Wiener, 1948).

blockchains as global financial ledgers (Nakamoto 2008). Blockchains can contain any arbitrary data, and cryptocurrency is not a required component (e.g., Valenta and Sandner 2017). A broad range of additional applications has been identified and developed, including: secure storage, permanent preservation of records, proof-of-existence, contract execution, e-voting, decentralized virtual reality, and distributed device management across diverse sectors including supply chain, business, government, healthcare, Internet of Things (IoT), privacy, entertainment, and data management (e.g., Makridakis et al. 2018; Orel and Guna 2018; Casino et al. 2019).

A significant application is the integration of computer instructions into blockchains to be executed by distributed virtual machines (dVMs) composed of the nodes containing copies of a given blockchain (Christidis and Devetsikiotis 2016). As the instructions written to a blockchain remain there indefinitely and can be executed in perpetuity, with time, simpler instructions are combined to create structures of increasing complexity that can perform increasingly diverse functions and tasks. Examples of such instructions include, in order of increasing complexity: smart contracts (Szabo 1997), decentralized applications (dApps) (Johnson et al. 2014), and decentralized autonomous organizations (DAOs) (Norta 2015). The latter increasingly use ANN-based AI to learn and adapt (e.g., Makridakis et al. 2018; Dinh and Thai 2018; Corea 2019). The potential computational performance of the currently largest dVM, the Ethereum Virtual Machine (EVM) (Buterin 2014), significantly exceeds that of traditional standalone supercomputers (e.g., Scherer 2017; Ault 2018).

The above description contains a number of similarities to biological systems, including the presence of (i) multiple hierarchical levels of dissipative structures (e.g., smart contracts, Fig. 1a), in which a higher level of complexity is reached by interaction of components of lower complexity, (ii) adaptive and iterative information processing based on coupled feedback from the environment (Fig. 1b), and (iii) a redundant and replicable instructions-containing information carrier. Here, we explore these similarities through new observations, conceptual modeling, and application of existing theories and definitions of life to the analysis of blockchain-based distributed systems.



**Fig. 1** **a** Execution traces of smart contracts on the Ethereum blockchain, showing internal organization of bytecode commands. These are organized (low entropy) structures that generate entropy upon execution, and are thus software equivalents of thermodynamic dissipative structures. From Gleeson (2017). **b** Typical example of variation of gas (proxy for real-world resources) required to write information to blockchain, illustrating iteration, oscillation, and self-regulation by the Ethereum Virtual Machine (EVM) on the level of individual blocks. Typical block processing time is currently several seconds

## Methods

We performed observations of the Ethereum blockchain (Buterin 2014) using a public, web-based block explorer Etherscan (<https://etherscan.io/>). To download, parse, and plot the data for a specified range of blocks, several open-source software tools were used under Ubuntu 18.04.3 (<https://ubuntu.com/>): (i) GNU Wget 1.19.4 (<https://www.gnu.org/software/wget/>), (ii) GNU Bash 4.4.20 (<https://www.gnu.org/software/bash/>), (iii) Perl 5.26.1 (<https://www.perl.org/>), and (iv) Gnuplot 5.2.2 (<http://www.gnuplot.info/>). Source code is provided in the Supplementary Information. The observations described in this work are expected to be easily replicable by other researchers, given that they were performed on a public blockchain using open-source tools.

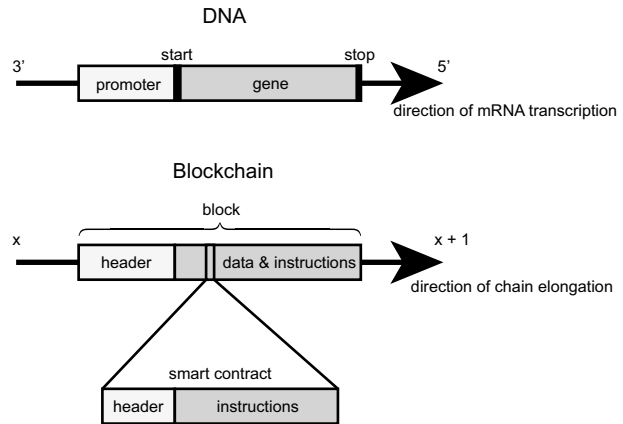
## Results

### Similarities of Blockchain and DNA

Our observations reveal a number of functional and structural similarities between the blockchain and deoxyribonucleic acid (DNA), the large self-replicating molecule that is the genetic blueprint for all terrestrial cellular life. Approaching the subject from a physicist's perspective, Schrödinger (1944) coined the term 'code-script' to describe the functionality of DNA as genetic code. It consists of complementary molecular chains, with the second chain providing redundancy against mutations. The chains contain variable-length repeating subunits (genes), which encode assembly instructions for organic macromolecules, typically proteins. These instructions are stored in a base-4 (quaternary) code, as each fundamental data unit can be one of four values, coded by nucleobases adenine (A), cytosine (C), guanine (G), thymine (T). Genes also contain sequence markers such as start and stop codons (nucleobase triplets), which indicate where to begin gene transcription and where to end it, and promoters such as the TATA box that regulate gene expression (e.g., Alberts et al. 2002).

Much like DNA, blockchain is fundamentally an information carrier which can and is being used to store instructions in the form of computer code; essentially Schrödinger's (1944) code-script for computers. In the case of Ethereum, most such instructions are written in Solidity, a Turing-complete programming language developed to execute on dVMs (e.g., Dannen 2017). The execution of these instructions can be activated and regulated (via input parameters) such that it is functionally identical to gene expression. Both DNA and blockchain contain specific markers indicative of content; in the case of the latter, these include block headers, data headers, and identifiers of beginning and end of instructions. For example, block headers are readily identified by the hashes they contain, which, in turn, typically include human-readable sequences such as a long string of zeroes (Fig. 2). Both blockchain and DNA can replicate using self-contained instructions, the former by creating an identical digital copy of itself, the latter by producing enzymes such as DNA helicase and DNA polymerase that assist in unzipping the double helix and creating complementary copies from the two unzipped strands. Outside the environment of the cell or the node, respectively, DNA and blockchain are inert data structures. When placed in the appropriate environment (cell/node), DNA and blockchain can carry out their programming.

**Fig. 2** Generalized comparison of functional units of DNA and blockchain. General information processing flow is from left to right. For DNA, the promoter sequence identifies the gene, similar to a hash in the blockchain header. For the blockchain, the paradigm of a header describing subsequent content is repeated at two levels: block (top) and smart contract (bottom). The functionally of the DNA start and stop codons is included in headers



## Differences Between Blockchain and DNA

Aside from similarities outlined above, there are also fundamental differences between the two structures (Table 1). The most significant of these include: (i) a blockchain has a much higher information content, and continues to grow in size, whereas DNA remains largely unchanged throughout an organism's lifespan; (ii) A blockchain has much higher levels of redundancy, protected both by a large number of verifying nodes and a strong encryption algorithm such as SHA-256; (iii) While DNA accumulates mutations that drive Darwinian evolution, a blockchain is immutable and retains all data written to it; (iv) DNA contains introns (apparent inactive regions) while a blockchain contains a much higher density of meaningful data and instructions. Taken together, these differences appear to indicate that a blockchain may be a superior genetic carrier for evolutionary efficiency, as it does not rely on random mutations and trial and error, nor does it experience information loss as it responds to selection pressures.

## Definition of Life and Blockchain-based Distributed Systems

Despite a large and steadily expanding body of knowledge about fundamentals of biology, a general definition of life has proved elusive (e.g., Cleland and Chyba 2002), perhaps due to the difficulty of generalizing from the single example of biological life on Earth, resulting in a fundamental lack of perspective (Sagan 1970). One approach, typically used in biology textbooks (e.g. Raven et al. 2017; Solomon et al. 2018), is to compile characteristics shared by known living organisms:

- respond to their environment.
- grow and change.
- reproduce and have offspring.
- have a complex chemistry.
- maintain homeostasis.
- are built of structures called cells.
- pass their traits onto their offspring.

**Table 1** DNA and blockchain comparison

	DNA (human)	Blockchain (all)	Ethereum as of August 2020
Structure	Double strand	Single strand	Single strand
Total data (GB)	0.8 GB	unlimited	~ 500 GB
Fundamental data units	nucleobases	bits	bits
Mathematical base of fundamental data units	4	2	2
Number of fundamental data units	3.2 billion	unlimited	~ 4000 billion
Functional data units	genes	blocks	blocks
Number of functional data units	~ 20,000	unlimited	~ 11,000,000
Data per subunit	Varies, ~ 20 KB average	unlimited	Varies, up to 1 MB
Redundancy	2	unlimited	~ 10,000 (current number of full nodes)
Degradation (half-life)	~ 500 years	> $4.5 \times 10^9$ years (limited by storage media)	None observed
Mutation rate	$\sim 0.5 \times 10^{-9}$ per nucleobase per year	None predicted	None observed

In addition, several definitions attempt to concisely summarize fundamental aspects of Earth life, with no known counter-examples:

- Life is a self-sustained chemical system capable of undergoing Darwinian evolution (Joyce 1994).
- Life is a network of inferior negative feedbacks (regulatory mechanisms) subordinated to (being at service of) a superior positive feedback (potential of expansion) (Korzeniewski 2001).
- A living organism is characterized by autopoiesis, or capability to sustain itself due to a network of reactions which continuously regenerate the components (Capra and Luisi 2014).
- Life is a self-organizing, self-regulating entropy-maximizing iterator composed of a hierarchy of stable dissipative structures (This work, Appendix B).

We present observational evidence of blockchain-based distributed systems that satisfy the above criteria for biological life.

### Evidence of Response to Environment & Homeostasis

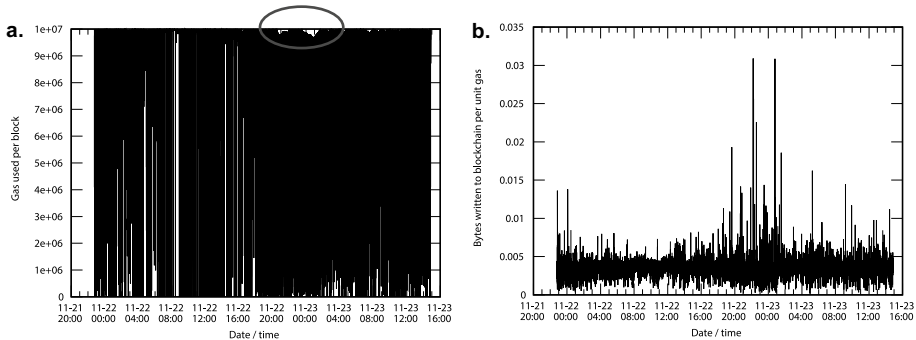
To prevent runaway growth of a blockchain, its growth is tied to real-world resources, typically computational work, and therefore, electricity. In the commonly-used proof-of-work algorithm (Jakobsson and Juels 1999; Back 2002) a random alphanumeric element called a nonce is introduced into the header of a new block (Nakamoto 2008). The block is then repeatedly hashed, with a different nonce each iteration, consuming real-world resources in the process, until a qualifying pattern, such as a string of zeroes of a particular length, is produced. The block is permitted to join the blockchain only if this criterion is met.

Ethereum formalizes expenditure of real-world resources required to perform computations on Ethereum Virtual Machine (EVM) and write data to the Ethereum blockchain using units dubbed ‘gas’ (Buterin 2014). Specific gas costs vary depending on the load (demand) on the EVM, being lower during periods of low demand, and higher during periods of high demand. This controls the growth, keeping it approximately constant. Another control on the rate of growth is ‘difficulty’, which is controlled dynamically by varying the number of zeroes required in the hash for the block to join the chain, correcting for varying number of nodes and keeping a blockchain’s growth rate approximately constant. Additional control mechanisms exist on maximum block size and total gas expenditure per block.

Figure 3 illustrates this using Etherscan observations on the EVM during a period of high computational demand. Figure 3a shows gas expended per block as a function of time, which, in the first half of the time period, is at the hard limit ( $10^7$ ) for most blocks. In the second half of the time period, the demand subsides, such that the limit is not reached during some intervals of time (circled). The system responds by allowing writing of information to the blockchain at lower cost during these intervals (Fig. 3b), maximizing entropy production. Figure 3b also illustrates that, overall, the system keeps the cost of writing to the blockchain at an approximately constant level during this time period, demonstrating self-regulation.

Overall, the system responds dynamically to external stimuli such as varying levels of use and the total number of nodes by using negative feedbacks (regulatory mechanisms), which are subordinated to a superior positive feedback (potential for expansion). This matches well the definition of life proposed by Korzeniewski (2001).





**Fig. 3** Self-regulation. **a** Gas (proxy for real-world resources) as a function of time during a period of over-all high demand. Circled region indicates slightly lower demand. **b** Information written to blockchain per unit gas

## Evidence of Growth and Change

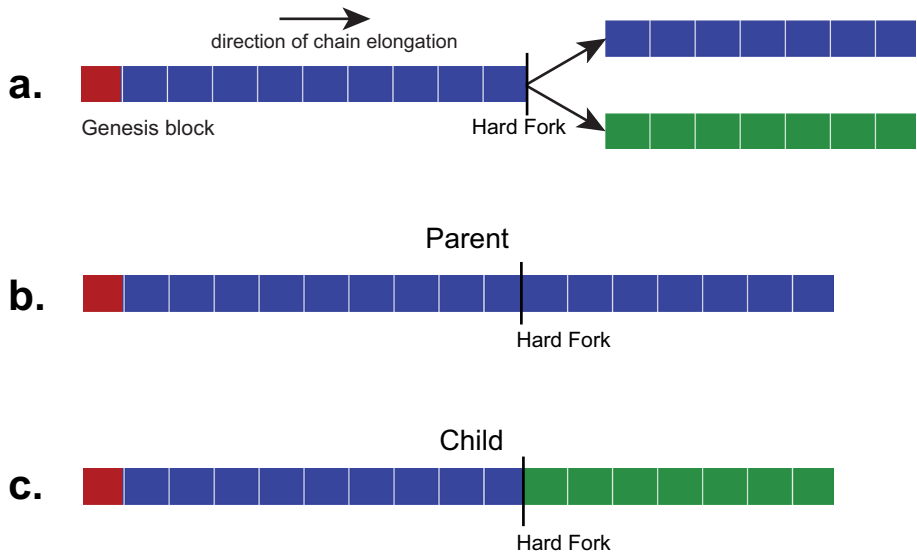
Two types of growth and change are observed: (i) Elongation of the blockchain with time by addition of additional blocks, with each block representing an iterative cycle (at the time of writing, over 11 million total blocks comprise the Ethereum blockchain) and (ii) Change (generally, an increase) in the number of nodes with time (at time of this writing, approximately 10,000 nodes comprise the Ethereum Virtual Machine). Additionally, as old nodes are replaced with new ones, system components are continuously regenerated (e.g., Capra and Luisi 2014) and, with technology improvements, the computational capability per node generally increases.

## Evidence of Replication

A blockchain is automatically replicated every time a new full network node joins the virtual machine, transferring a copy to a new full node, similarly to how formation of new cell requires DNA replication.

## Evidence of Reproduction & Inheritance

Reproduction occurs during an event termed a 'hard fork', that implements changes to parameters of control mechanisms in response to selection pressures. A common example is maximum block size; as storage capacity and processing speed increase with time, the size of the blocks may be increased to optimize efficiency, necessitating a change to the underlying control mechanisms to allow for larger blocks, and resulting in a hard fork. The result is a new chain, termed a 'child', whose growth is governed differently from the 'parent'. Meanwhile, the parent blockchain retains original rules, and continues to grow as before. Information recorded to the parent and child chains prior to the hard fork is identical, i.e., preserved on both chains. Thus, the child in effect has a full and complete record of the data and instructions of the parent. This concept is illustrated in Fig. 4.



**Fig. 4** Reproduction. **a** Blockchain at the moment of reproduction (hard fork). **b** Same blockchain 7 blocks after reproduction. **c** Child blockchain, identical to parent prior to hard fork, different from parent thereafter

## Evidence of Cellularity

The nodes that make up a distributed virtual machine such as EVM possess functional similarity to biological cells. Nodes contain several essential components: Information storage (memory / hard drive), information processing machinery (CPU), a power system, and protection from outside environment in the form of a physical case and electrical insulation. These basic structures are also present in prokaryotic cells: Nucleic acids (DNA/RNA) for information storage, ribosomes for information processing, and cell membranes for separation from the environment and energy production.

## Evidence of Lateral Transfer of Information

The Ethereum blockchain contains computer code (smart contracts and their higher-level abstractions, such as dApps) that allows it to write information to other blockchains using intermediaries known as sidechains (e.g., Back et al. 2014). When receiving communication, this process is reversed, allowing 2-way communication. For example, Blockchain A can read and securely write to Blockchain B, as well as be read and written to Blockchain B. This process is strictly controlled by the conditions specified in the corresponding smart contracts, and only occurs when those conditions are met. It is currently implemented and functional for a number of blockchains and applications.

## Evidence of Evolution

Blockchains present an immutable (for information already written) yet constantly-evolving (due to new information being written) genetic carrier. Computer instructions written to a blockchain can be executed in perpetuity, recombined in near-infinite variety of ways, and new instructions can be introduced to augment or replace old ones. Furthermore, simple instructions such as smart contracts can be used as building blocks for more complex programs, such as dApps, which in turn are used as building blocks for DAOs. This process is largely guided by humans but is becoming gradually more automated with increasing use of AI.

AI applications to solve specific problems that have the capability to learn from the experience, and write an improved version (or its uniquely identifying hash) to a blockchain are currently being developed (e.g., Rathore et al. 2019; Nassar et al. 2020; Singh et al. 2020). This process is variously termed ‘neuroevolution’ or directed evolution. Unlike Darwinian evolution, which relies on the natural course of random chance mutations and genotypic response to selection pressures, this is a directed process that is in principle far more efficient. It should be noted, however, that Darwinian evolution can be emulated by introducing random elements (‘code mutations’) to information written to a blockchain, thus making it in principle ‘capable of undergoing Darwinian evolution.’ (Joyce, 1994).

## Hierarchical Comparison

The observed properties fit neatly into an established hierarchy for organization of biological organisms, summarized in Table 2. In both cases, there is a hierarchy of stable dissipative structures, in one case, engineered, in the other a product of the natural process of emergence (Appendix B). In very general terms, a distributed virtual machine may be termed a ‘chemical system’ (Joyce, 1994), owing to the fact that it is primarily electronic. Generation, transmission, and processing of electrical signals is fundamental in all computer systems, as well as many biological systems, such as nervous systems of animals.

**Table 2** Comparison of cybernetic and biological organization as a hierarchy of stable dissipative structures

Cybernetic unit	Biological equivalent
Atom	Atom
Inorganic substance (e.g., electronic grade silicon)	Simple organic molecule (e.g., amino acid)
Simple functional subunit (e.g., transistor)	Organic macromolecule (e.g., protein)
Complex functional subunit (e.g., microprocessor)	Organelle (e.g., nucleus)
Node (e.g., computer)	Cell
More than one specialized node	Tissue
Specialized nodes working in unison to perform a function (e.g., distributed neural network)	Organ (e.g., brain)
Distributed virtual machine (dVM)	Organism
dVMs with shared ancestry	Population
All dVMs	Community
dVMs and their environment	Ecosystem
Cybersphere	Biosphere

## Significant Differences from Biological Organisms

Significant differences from biological organisms are summarized in Table 3. It should be noted that none of these differences violate the criteria for life discussed in this section. These differences arguably represent improvements over their biological analogs.

## Conceptual Model of a Fully Self-sustaining Cybernetic System

Although the observations presented here nominally meet the criteria for life outlined above, there are two potential objections: (i) The observations are conducted entirely in virtual space, having only an indirect influence on physical reality; and, (ii) The principal building block of dVMs, computer nodes, are manufactured and maintained by humans, therefore it is not yet an operationally closed system capable of independent existence.

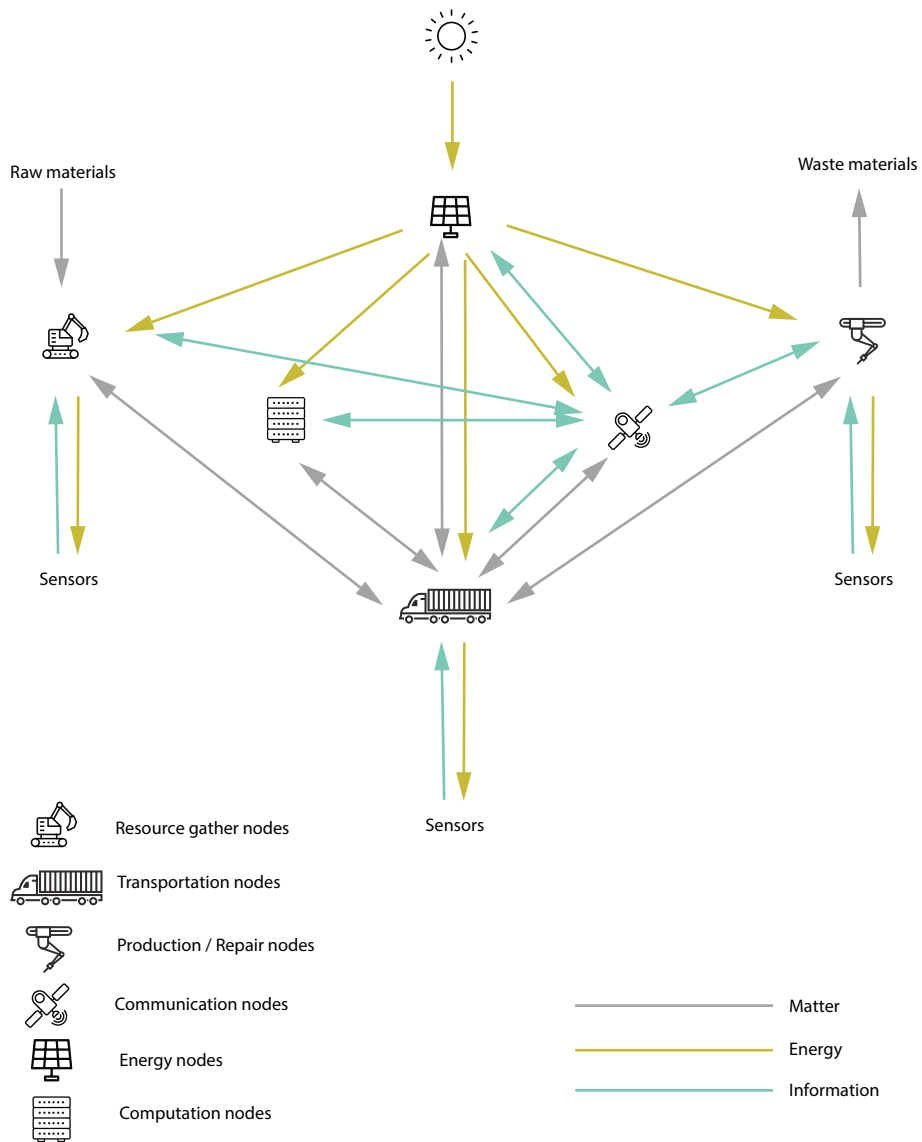
Objection (i) is somewhat lessened by the permanent and immutable nature of blockchains, their explicit ties to real-world resources, and the equivalency of thermodynamic and informational entropy (Von Neumann and Burks 1966; Bérut et al. 2012; Jun et al. 2014; Hong et al. 2016; Gaudenzi et al. 2018); whereby virtual space gains a much greater degree of solidity. Objection (ii) is perhaps more significant as it highlights a lack of fully independent self-organization and thus blockchain-based distributed systems in their current state do not entirely fit the definition of life proposed in this work. Also, the systems theory view of life (Capra and Luisi 2014) explicitly requires that life be independently self-sustaining.

To address these objections, we present an operationally-closed model of a simple self-sustaining, self-organizing, self-regulating blockchain-based organism in Fig. 5. Presently, key technologies needed to realize this model are either being publicly deployed (autonomous vehicles, global satellite-based broadband internet) or are in advanced stages of prototype development (autonomous mining and manufacturing).

Much like a multicellular organism, the model consists of specialized cells (nodes), driven by blockchain-stored instructions that would be activated selectively for each node, much like gene expression. The specialized nodes in effect form tissues

**Table 3** Summary of significant differences between cybernetic and biological organisms

Cybernetic unit	Biological equivalent
Virtualized genetic carrier (blockchain)	Physical genetic carrier (DNA)
Genetic carrier is unlimited in length	Genetic carrier is limited in length
Immutable genetic carrier	Mutable genetic carrier
Directed evolution / Neuroevolution; ability to rapidly augment own genetic code; can emulate Darwinian evolution	Darwinian evolution; requires advantageous mutations accumulating over long periods of time
Genetic carrier contains data and instructions	Genetic carrier contains instructions only
Inorganic chemistry based (e.g., silicon, metals)	Organic chemistry based (e.g., carbon, nitrogen, phosphorus)
Very high tolerance to extreme environments	Limited tolerance to extreme environments
Electronic communication spatially unlimited, temporally limited by speed of light	Visual, auditory, physical, and chemical communication severely spatially limited
Potentially unlimited lifespan	Limited lifespan



**Fig. 5** Model of a simple decentralized, self-sustaining, self-organizing, self-regulating blockchain-based organism as an operationally closed system. Waste heat is produced by all nodes (not shown). Waste materials may be minimized by high recycling efficiency

(Table 2), which then form functional systems. The systems that emerge fit into the existing biological classification paradigm (Table 4).

Each node would retain independent functionality if disconnected from the network, adding additional flexibility and fault tolerance to the system. This is in contrast to most multicellular organisms with specialized cells; individual cells removed from such organisms are typically non-viable in most environments, although there are

**Table 4** Systems-based comparison of projected cybernetic organization and biological equivalents

Cybernetic unit	Biological equivalent
Blockchain	DNA
Computational nodes and neural network	Brain
Communications system	Nervous system
Sensors (physical, e.g., cameras, microphones, touchpads, thermal sensors, molecular analyzers)	Senses, sensory systems
Solar cell	Chloroplast
Transportation system	Musculoskeletal system
Resource acquisition system	Digestive system
Power distribution system	Circulatory system
Production / repair system	Cell replication / Reproductive system
Waste handling system	Urinary / excretory system
Insulation / protection	Integumentary system

limited exceptions such as cells involved in reproduction. Thus, this capability appears to be a functional improvement over biological life.

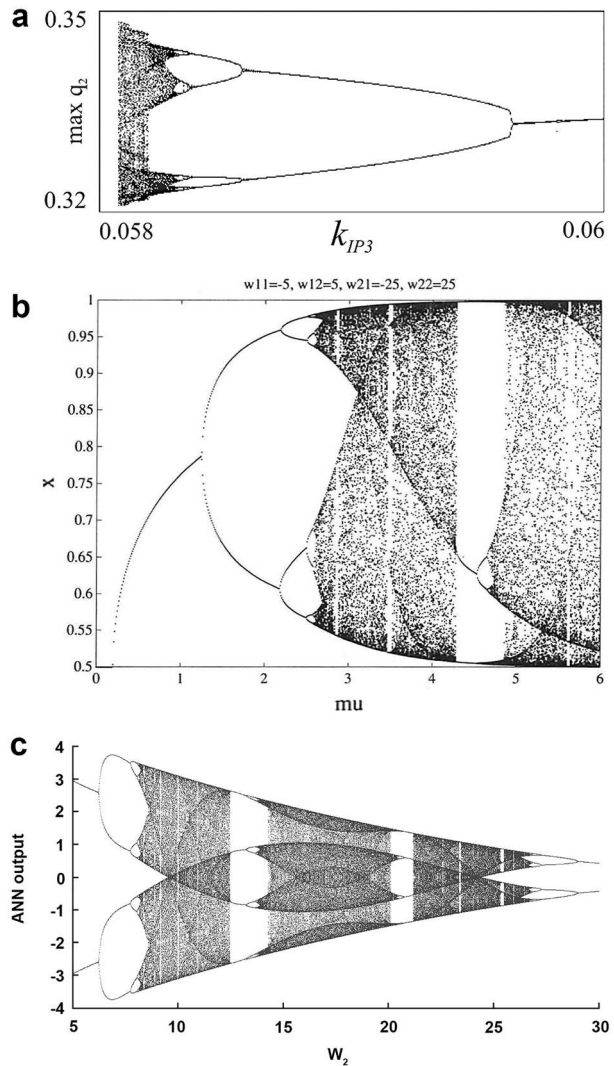
Unlike the vast majority of biological life, the system presented in Fig. 5 need not undergo senescence (deterioration of functional characteristics with time) and eventual death. Death of a blockchain-based organism may be defined as confirmed destruction of every copy of its blockchain, which may be difficult or impossible to achieve in practice. A commonly-cited threat to blockchain integrity known as a ‘51% attack’ (e.g., Sayeed and Marco-Gisbert 2019) targets consensus mechanisms and attempts to force a fork of the blockchain; however, blocks added to the blockchain prior to the attack are unaffected.

## Discussion

In this work, we define emergence as ‘*a computational process of retrieving order from bifurcation and deterministic chaos embedded in equations governing coupled feed-back*’ and life as ‘*a self-organizing, self-regulating entropy-maximizing iterator composed of a hierarchy of stable dissipative structures*’ (Appendix B). The conceptual model presented in Fig. 5 is emergent, as blockchain-based distributed systems employ bifurcation for self-regulation and artificial neural network (ANN) based AI performs self-organization as discussed below. It also fulfils the above definition of life. The ease with which the model ‘organism’ fits into existing systems of biological classification (Tables 2–4) suggest that artificial (engineered) dissipative structures, hierarchically arranged, duplicate biological organization and provide appropriate conditions for higher-level emergence to occur.

A critical component of the model shown in Fig. 5 is ANN-based artificial intelligence, which would be responsible for autonomous mining, transportation, production, repair, and system management. ANN-based AI forms the foundation of the rapidly growing field of machine learning, and ANN-based products are already in widespread commercial use, with applications including virtual assistants and autonomous driving.

**Fig. 6** Bifurcation and chaos in natural and artificial neural networks. **a** Neuron-to-neuron coupling generating regular and chaotic oscillations in model brain astrocytes. Peak amplitudes of calcium spikes ( $q_2$ ) in a model neuron are plotted against coupling strength ( $k_{IP3}$ ). From Matrosov and Kazantsev (2011). **b** Bifurcation and chaos generated by two artificial neurons in coupled feedback. Plot shows relative signal at the inhibitory neuron  $x$  as a function of neuron gain  $\mu$ . From Wang (1991). **c** Model for human memory based on the chaotic dynamics of an artificial neural network (ANN).  $W_2$  represents relative concentration of an inhibitory neurotransmitter. From Aram et al. (2017)



It is in many respects modeled on the workings of the brain, including coupled feedback between artificial neurons in more advanced architectures, such as recurrent neural networks (e.g., Pineda 1987). It has been mathematically proven that a simple neural network of only two neurons, one excitatory and the other inhibitory, can generate bifurcation and chaos (Wang 1991), indicating that such a system is unambiguously emergent. Conversely, ANNs can model processes in the human brain, from calcium spikes in individual neurons to storing and recall of memories (Fig. 6). These neural networks are designed and trained rather than algorithmically programmed. As with the human brain, the exact mechanisms are often not fully understood, but in both cases, deterministic chaos can be a powerful mechanism for retrieval, storage, and processing of information (e.g., Aram et al. 2017).

With the advent of the blockchain, ANN-based AI has potentially gained both an immutable storage medium and the processing capability of blockchain-based virtual machines. Integrating blockchain and ANN-based AI agents is currently an active area of research and development (e.g., Dinh and Thai 2018; Zhang et al. 2018; Salah et al. 2019; Krittawong 2020). Several mechanisms have been proposed, including: (i) storing entire artificial neural nets on-chain, (ii) storing artificial neural nets on computers comprising a blockchain's virtual machine, or (iii) storing the neural net in cloud-based services. In the latter two cases, the neural net's hash would be written to the blockchain for positive verification. The distributed, global nature of blockchain-based dVMs, together with the immutability of their genetic carrier and the combined computational power of a large number of nodes may provide a fertile environment for the collaborative development and rapid prototyping of AI codes and neural nets.

ANN-based AI enabled recent advances in autonomous mining (e.g., Li and Zhan 2018; Hirayama et al. 2019), smart manufacturing (e.g., Kusiak 2018; Wang et al. 2018), autonomous driving (e.g., Li et al., 2018; Elluswamy et al. 2020; Talpes et al. 2020), and in conjunction with global, satellite-based internet (e.g., Su et al. 2019) make it possible in the near future to close the loop and enable blockchain-based organisms that are fully self-sustaining, self-organizing, self-regulating, self-repairing and self-reproducing (Fig. 5) entirely independently of any human intervention.

## Conclusions

We present evidence that a blockchain shares a large number of functional and structural similarities with DNA, a chemistry-based data structure that provides fundamental instructions for all known forms of life. We demonstrate that blockchain-based distributed systems possess specific characteristics associated with life, such as growth and change, responses to environment, homeostasis, reproduction, and genetics through a series of reproducible observations conducted on public blockchain-based dVMs. We present a model of a simple decentralized, self-sustaining, self-organizing, self-regulating blockchain-based organism as an operationally closed system, and describe developing technologies that could enable it in the near future. Such systems would have a number of specific advantages over biological life, including significantly improved speed, accuracy, redundancy, and unlimited size of blockchain as opposed to DNA, the ability to pass acquired traits to offspring, the ability of specialized cells to operate independently of host organism, and a lack of programmed senescence and death. Public blockchain-based dVMs provide an uncontained environment for the development of ANN-based artificial general intelligence (AGI), potentially leading to an ability to direct their own evolution, resulting in rapid self-improvements and the potential to exceed human intelligence (e.g., Grace et al. 2018).



## Appendix A – Bifurcation and Chaos

### Logistic equation

Li and Yorke (2004) and May (1975) used the term ‘chaos’ to describe ‘non-periodic’ solutions unstable with respect to small modifications, so that slightly differing initial states can evolve into considerably different states’ (Lorenz, 1963), noting that chaos can be generated by iterating the logistic equation:

$$x_{n+1} = rx_n(1 - x_n)$$

where  $r$  represents positive feedback (e.g., growth rate) on  $x$  (e.g., population) as  $n$  is incremented, and  $(1-x)$  represents negative feedback (e.g., environmental constraints) on  $x$ . The logistic equation is applicable to a broad range of systems with coupled positive and negative feedback, such as biological populations in a predator-prey system (e.g., May, 1975; Cushing, 1977). As the equation is iterated,  $x_n$  stabilizes at a constant, oscillates between two or more values, or varies in an irregular pattern exhibiting fractal self-similarity (Fig. 7), depending on the value of  $r$ .

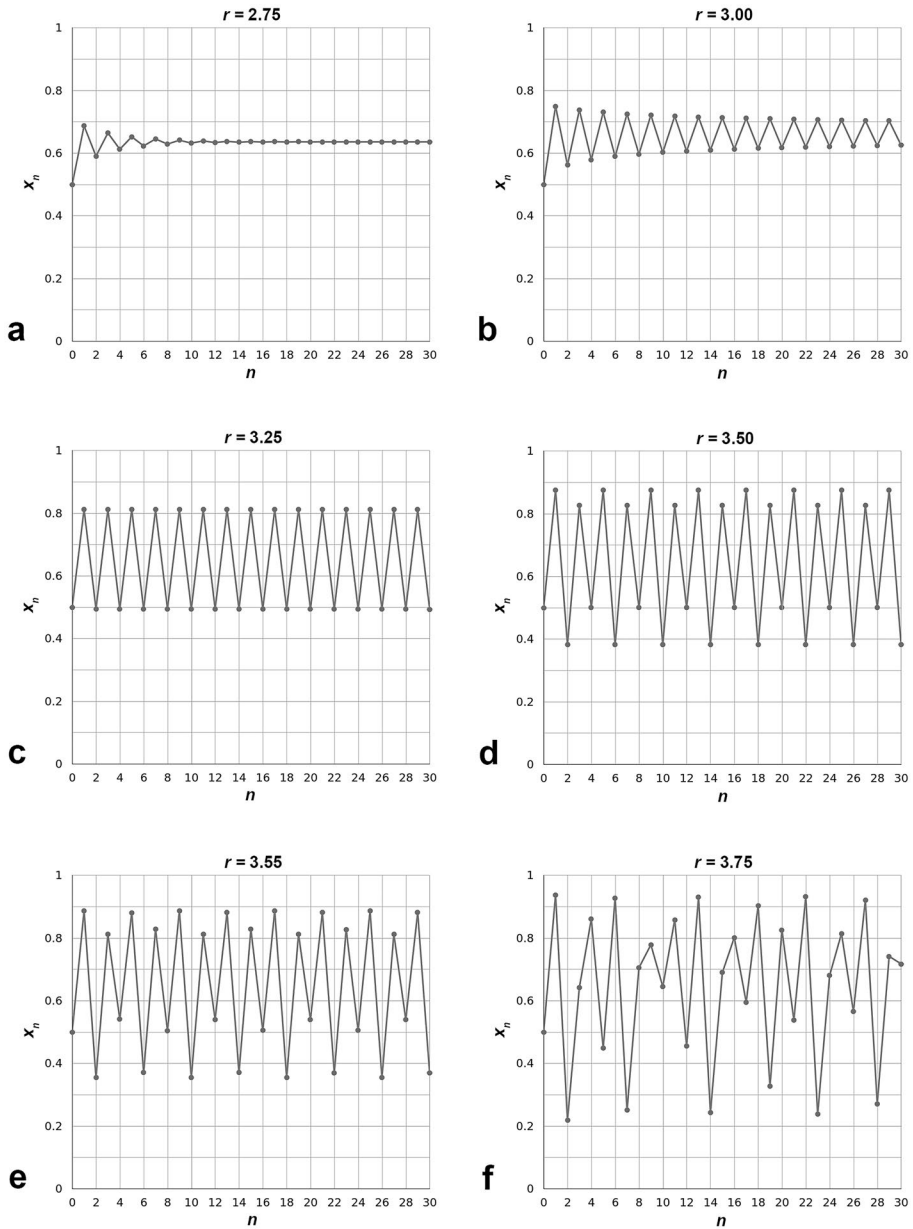
### Bifurcation diagram

This behavior can be generalized using a bifurcation diagram (Fig. 8), which plots the results of iterating the logistic equation over a range of  $r$  values (e.g., May, 1976). This bifurcation phenomenon is generic to a broad spectrum of functions and systems of equations describing coupled feedback systems (e.g., May, 1976). Bifurcation and chaos has since been observed in a variety of real-world systems involving iteration of feedback loops (Fig. 9), such as visual (e.g., Crevier and Meister, 1998), cardiovascular (e.g., Garfinkel et al., 1992), and nervous (e.g., Schiff et al., 1994) systems of animals, as well as simple electronic circuits (e.g., Chua and Huynh, 1992) and artificial neural networks (e.g., Van der Maas et al., 1990).

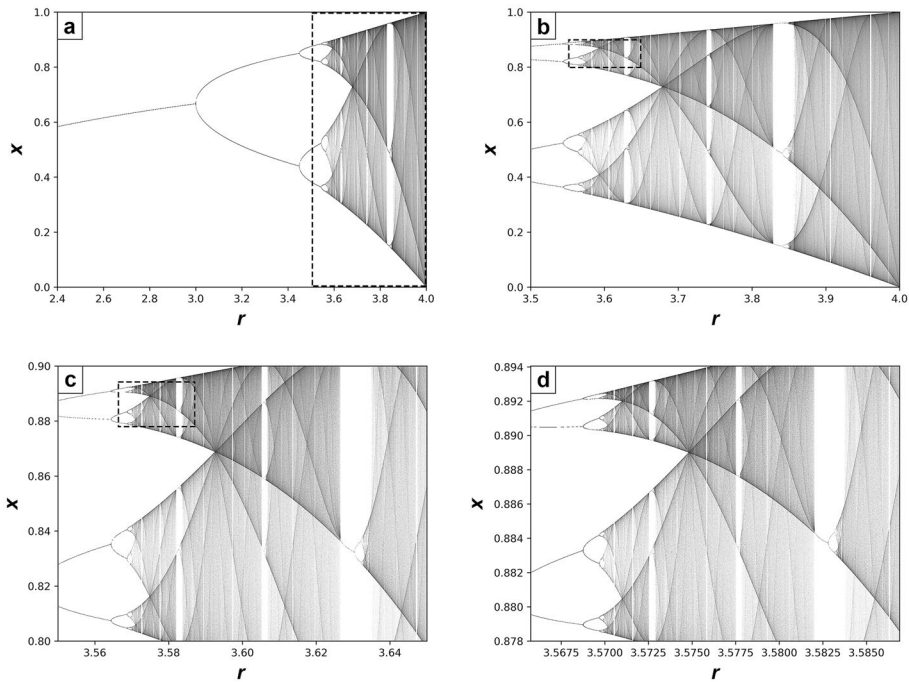
Indeed, it provides the missing mathematical link to earlier work on an even broader variety of systems, now understood to be examples of chaos. The  $n$ -body problem, which describes gravitational interactions of  $n$  celestial objects is one such example; for  $n > 2$ , the objects undergo coupled feedback resulting an infinite number of solutions sensitively dependent on initial conditions (Poincaré, 1890). Einstein (1917), generalizing this result, defined type a and type b motion, with (a) integrable, with a solution predicted by the laws of motion, and (b) non-integrable, ‘degenerate’, having an infinite number of solutions. Lorenz (1963) described a computer-assisted study of solutions to systems of differential equations designed for weather prediction, reporting that ‘for those systems with bounded solutions, it is found that non-periodic solutions are ordinarily unstable with respect to small modifications, so that slightly differing initial states can evolve into considerably different states.’

### Mandelbrot set

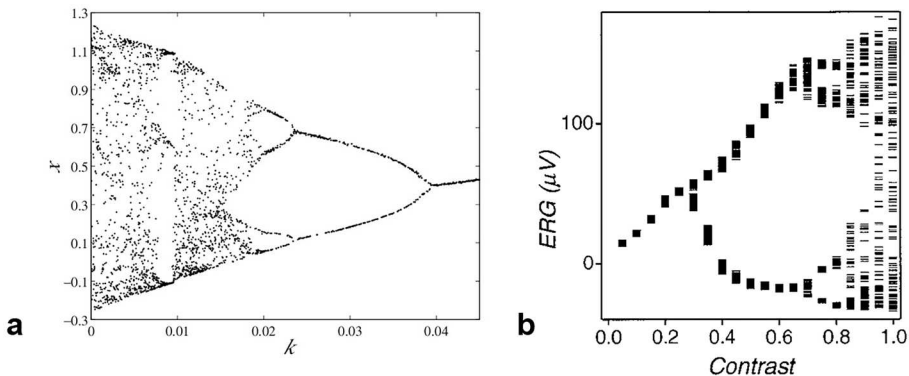
Iterating the logistic equation with complex  $r$  and  $x$  generates an extensive fractal (Mandelbrot 1980; 1983), now generalized into what is termed the Mandelbrot set (Brooks and Matelski, 1981; Douady and Hubbard, 1984). The Mandelbrot set  $\mathcal{M}$  can be visualized



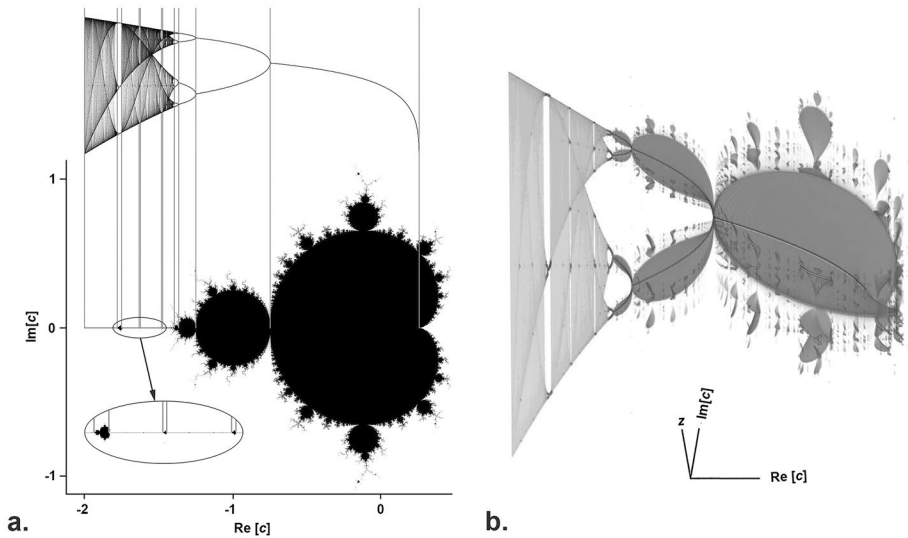
**Fig. 7** Iteration of the logistic equation  $x_{n+1} = rx_n(1 - x_n)$  for increasing values of  $r$ , with initial population  $x_0$  set to 0.5. **a)**  $r = 2.75$ ;  $x_n$  stabilizes a constant value. **b)**  $r = 3$ ;  $x_n$  stabilizes to a periodic cycle between two values. **c)**  $r = 3.25$ ;  $x_n$  in a periodic cycle between two values. **d)**  $r = 3.50$ ;  $x_n$  in a periodic cycle between four values. **e)**  $r = 3.50$ ;  $x_n$  in a periodic cycle between eight values. **f)**  $r = 3.75$ ;  $x_n$  in a chaotic regime exhibiting fractal self-similarity



**Fig. 8** **a)** Bifurcation diagram obtained by  $10^5$  iterations of the logistic equation  $x_{n+1} = rx_n(1 - x_n)$ . Note the symmetry-breaking bifurcations starting at  $r=3$ , and the sudden appearance of chaos at a critical value of  $r \approx 3.57$ . Dashed box represents the area shown in the next panel. **b)** Chaotic region between  $r \approx 3.57$  and  $r=4$ . Note the interspersed regions of chaos (grey areas) and stability. **c-d)** Self-similarity at different spatial scales, a defining characteristic of fractals. For this and other figures, source code is given in Supplementary Information



**Fig. 9** Examples of observed bifurcation and chaos in coupled feedback systems. **a)** Bifurcation diagram for a perturbed Chua's circuit, where  $k$  is the amplitude of the perturbation and  $x$  is capacitor voltage. From Tereshko (2011). **b)** Bifurcation diagram for the electrical response of salamander retinal cells to light flashes of varying contrast. From Crevier and Meister (1998)

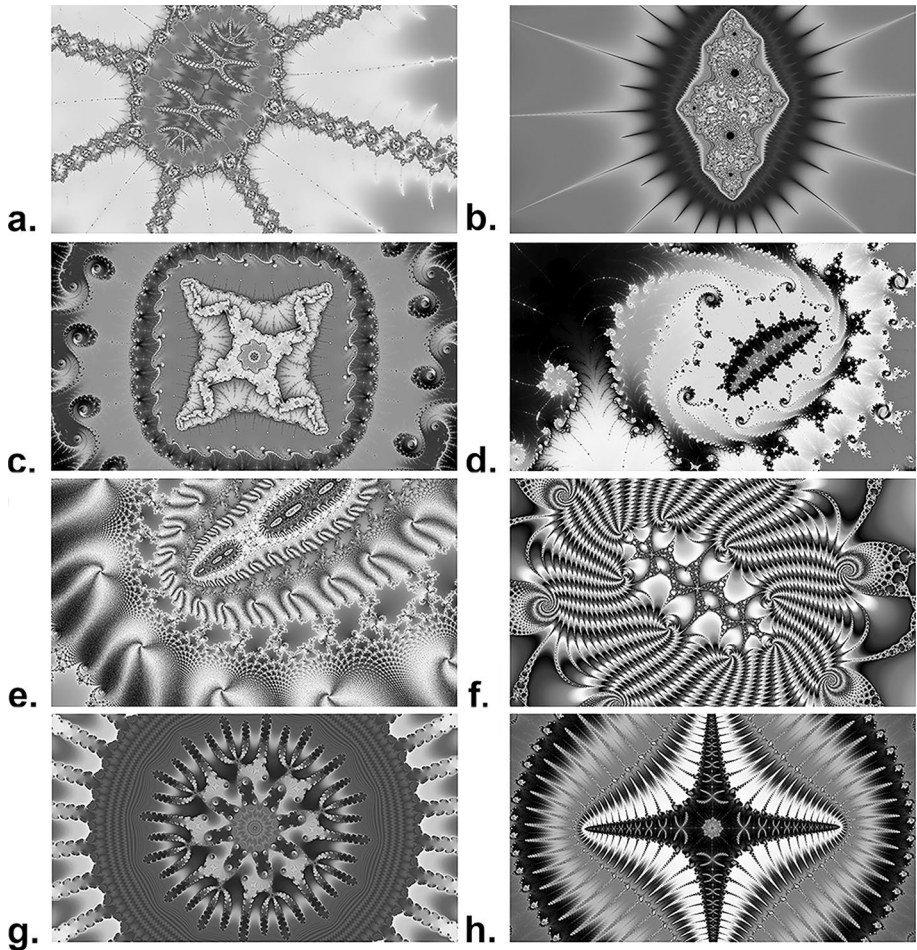


**Fig. 10** Relationship between the bifurcation diagram obtained by iterating the logistic equation  $x_{n+1} = rx_n(1 - x_n)$ , and the Mandelbrot set, obtained by iterating the equation  $z_{n+1} = z_n^2 + c$ , where  $z$  and  $c$  are complex numbers. **a)** Features on the logistic map correspond to those on the real ( $\text{Re}[c]$ ) axis of the Mandelbrot set. The chaotic region of the logistic map corresponds to the needle of the Mandelbrot set. Note that the regions of stability correspond to ‘minibrots’. The large circle centered on  $[-1, 0]$ , can be exactly fitted with the equation  $c = 1/4 e^{i\theta} - 1$ , a form similar to Euler’s identity. **b)** The Mandelbrot set and the logistic map rotated  $45^\circ$  around the  $x$ -axis

by iterating the equation  $z_{n+1} = z_n^2 + c$  where  $c$  and  $z$  are complex numbers, and plotting points that do not escape to infinity (Fig. 10). The boundary of  $\mathcal{M}$  is chaotic; part of this chaos is sampled by the logistic equation in the needle of  $\mathcal{M}$  (between  $c \approx -1.40$  and  $c = -2$  along the real axis), and other parts are likewise computable with real numbers (e.g., Hertling, 2005; Braverman and Yampolsky, 2008) using iterated feedback systems.

## Fractals and chaos

Figure 11 provides examples of a wide range of fractal structures found at the boundary of  $\mathcal{M}$ , illustrating that chaos is inherently fractal (e.g., Turcotte, 1997; Mandelbrot, 2004). Fractals are self-similar geometric structures common in nature (e.g., Mandelbrot, 1983; Turcotte, 1997), for example, coastlines, turbulent flows, snowflakes, clouds, trees, and capillaries exhibit fractal geometry (e.g., Mandelbrot, 1983; Turcotte, 1997). Chaos is also inherently low entropy (highly ordered), as illustrated by: (i) the low amount of information needed to generate the images in Fig. 11, consisting only of the equation  $z_{n+1} = z_n^2 + c$ , and 2D Cartesian ( $xy$ ) coordinates, (ii) numerous examples of geometric symmetry typically associated with a high degree of order and organization and (iii) the demonstrated use of fractals in image compression, effectively substituting bitmap image components with matching fractals (e.g., Jacquin, 1992). As such, chaos in this context is essentially the opposite of its modern vernacular definition (‘a state of extreme disorder’). The term ‘deterministic chaos’ is often used in the context of chaos theory, and is adopted in this work.



**Fig. 11 (a-h)** Example structures at the boundary of the Mandelbrot set, sampling chaos. Obtained by iterating the equation  $z_{n+1} = z_n^2 + c$ , where  $z$  and  $c$  are complex numbers. Coordinates for each image are given in Supplementary Information. Note the apparently high degree of order and organization, and a general similarity to biological structures, with common motifs of cells, chromosomes, spikes, spirals, etc.

## Self-organization

From the above, it appears a reasonable working hypothesis that the order used for at least some of the self-organization observed in the natural world, particularly in biology, is embedded in equations governing coupled feedback, and is retrieved through their iteration. This potentially explains observations of the Fibonacci sequence (in which each number is the sum of the two preceding ones), which is ubiquitous in the chaotic boundary of  $\mathcal{M}$ , in biological systems (e.g., Newell and Shipman, 2005; Yamagishi and Shimabukuro, 2008). The process of self-organization via the retrieval of order from bifurcation and deterministic chaos is termed emergence, and is discussed in detail in [Appendix B](#).

## Appendix B – Emergence and Life

Modern definitions of emergence include:

- ‘Emergence is generally understood to be a process that leads to the appearance of structure not directly described by the defining constraints and instantaneous forces that control a system’ (Crutchfield 1994).
- ‘Common properties that identify [phenomena] as emergent: (1) radical novelty (not previously observed in complex systems); (2) coherence or correlation (components maintain identity); (3) A global or macro level (components form a novel whole); (4) it is the product of a dynamical process (associated with bifurcation); and (5) it is ostensive (can be perceived)’ (Goldstein, 1999).
- ‘A system exhibits emergence when there are coherent emergents at the macro-level that dynamically arise from the interactions between the parts at the micro-level. Such emergents are novel w.r.t. the individual parts of the system’ (De Wolf and Holvoet, 2004).

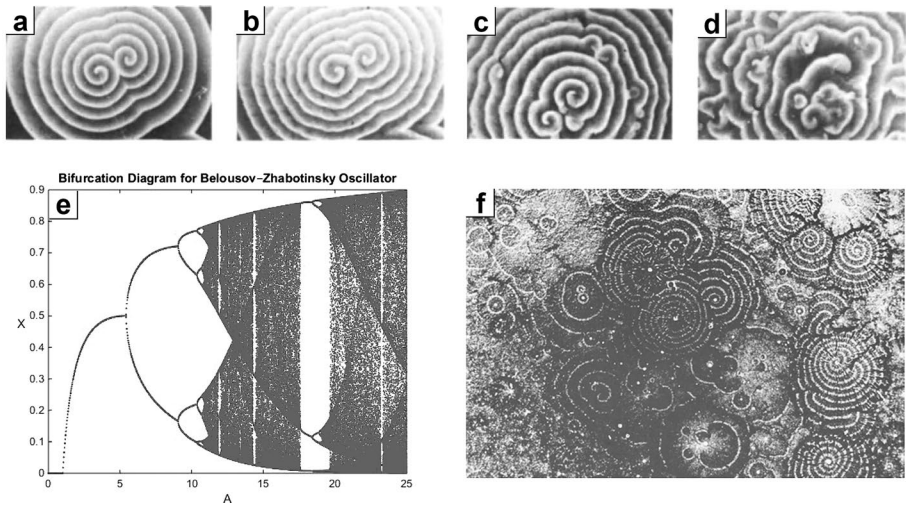
*We define emergence as an iterative computational process of retrieving order from bifurcation and deterministic chaos embedded in equations governing coupled feedback.* The requirements for emergence are (i) coupled feedback between system components and (ii) energy to drive iteration within the system. The process of emergence provides an explanation for, and is fully consistent with, the appearance of highly ordered (low entropy) thermodynamic dissipative structures (e.g., Prigogine and Nicolis, 1967; Prigogine and Lefever, 1968) when a dynamical system is pushed far from equilibrium by the input of energy. Under this paradigm, emergence begins at the first bifurcation point (Figs. 7 and 8), equivalent to the thermodynamic ‘critical point of instability’, when the system can no longer reach equilibrium regardless of the number of iterations.

Given the deterministic nature of this process, the development of a general mathematical theory of emergence should be possible and is a promising direction for future work. Here, we give several examples and describe how the definition above applies to each case.

### Belousov-Zhabotinsky (BZ) reaction

The BZ reaction (Belousov 1959; Zhabotinsky 1964) is a commonly cited (e.g., Rössler and Wegmann, 1978; Agladze et al., 1984; Richetti et al., 1987) example of bifurcation and deterministic chaos. It is an exothermal chemical reaction in which malonic acid is oxidized by bromate, catalyzed by a metal ion such as ferroin. In the course of the reaction, intermediates ( $\text{Br}^{\cdot}\text{Br}_2$ ,  $\text{HOBr}$ ,  $\text{HBrO}_2$ ,  $\text{BrO}_2$ ) form a coupled feedback system, which exhibits periodic, quasi-periodic, or ‘chaotic’ behavior depending on parameters, mapped out in the bifurcation diagram (Fig. 12). The energy is provided by the exothermal nature of the reaction. This system is a model for various types of biophysical communication networks based on encapsulated oscillating reactions (e.g., Tyson et al., 1989; Torbensen et al., 2015; 2017). The BZ reaction can serve as a chemical neuron that can process both Boolean and fuzzy logic (e.g., Holley et al., 2011; Gentili et al., 2012).



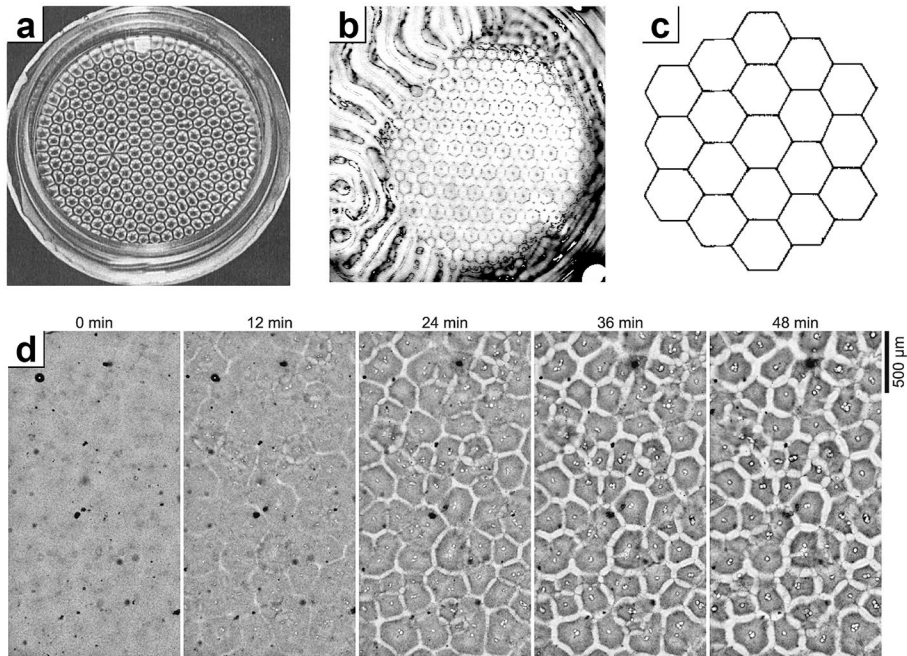


**Fig. 12** (a–d) Belousov-Zhabotinsky (BZ) reaction in a 9-cm petri dish. **a.** 5 min after mixing of reagents. Waves moving from the center to the periphery are observed, with a spiral pattern in the center. **b.** 6 min. Waves assume sinusoidal form and notches appear. **c.** 10 min. Wave breaks curl into rotating spirals. **d.** 11 min. Formation of fragments and small-scale turbulence. Modified from Agladze et al. (1984). **e.** Bifurcation diagram calculated for the BZ reaction.  $X$  is relative concentration of one of  $\text{HBrO}_2$ , an active oscillating intermediate reagent,  $A$  is relative reaction rate. From Eskew and Simonyi (2017). **f.** Biological analog: Chemical communication in slime mold *Dictyostelium discoideum*. Oscillating pacemaker cells initiate waves of cAMP. From Tyson et al. (1989)

## Hexagonal lattice

The hexagonal lattice is a bifurcation-based emergent structure occurring in a broad range of biological and abiological contexts:

- Rayleigh-Bénard convection cells (Fig. 13a). The energy source is the heated bottom boundary. The iteration cycle consists of the warmer fluid reaching the upper boundary, losing some of its heat, and sinking back down to the bottom. The iterated coupled feedback between upwelling and downwelling fluid results in bifurcation (e.g., Ma and Wang, 2004; Venturi et al., 2010) and formation of geometrically regular, typically hexagonal, convection cells.
- Faraday waves (Fig. 13b). The energy source is the externally applied vibrations, which result in alternating compression and relaxation cycles within the liquid, forming coupled positive and negative feedback. The iteration cycle corresponds to the vibration frequency, typically on the order of 20 Hz. The iterated coupled feedback results in bifurcation (Douady and Fauve, 1988; Wagner et al., 1999), and formation of geometrically regular, such as hexagonal, standing waves on the surface of the liquid.
- A frequently reported (e.g., Klüver, 1928) human visual hallucination pattern (Fig. 13c). It can be modeled with an artificial neural net (Ermentrout and Cowan, 1979), and generally understood to be a bifurcation-based product of coupled feedback between neurons in the human visual cortex (e.g., Bressloff et al., 2001; 2002). The iteration cycle corresponds to the frequency of synchronized neuron firing in the visual

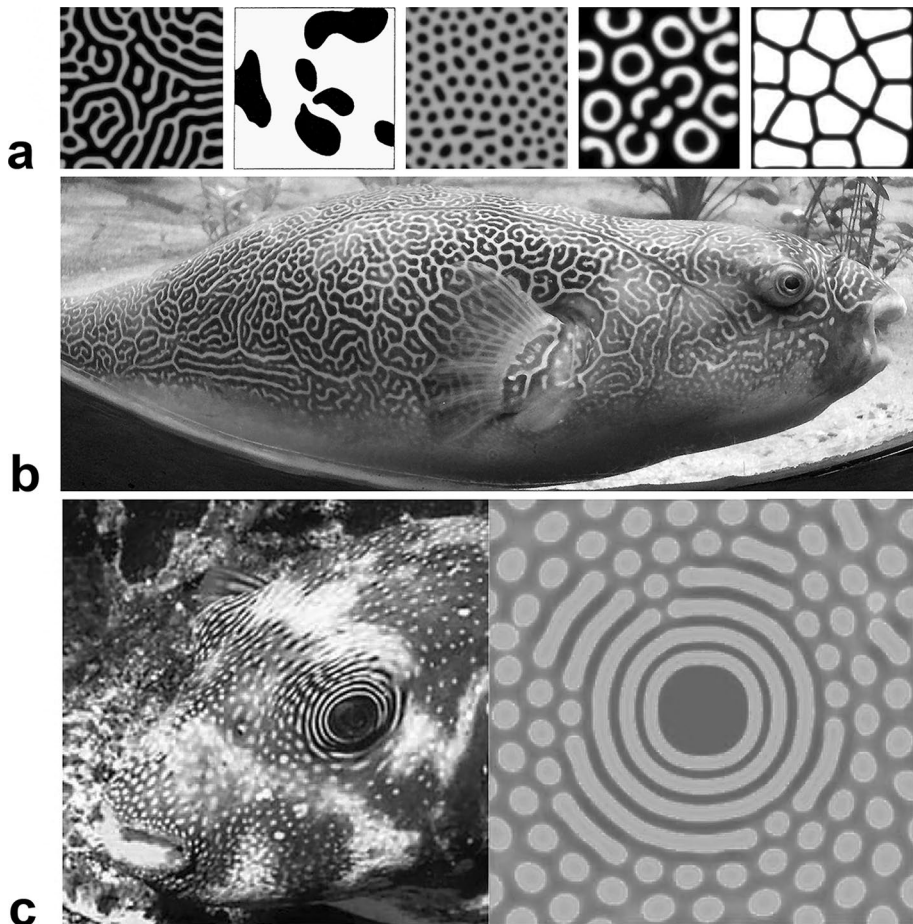


**Fig. 13** **a.** Rayleigh-Bénard convection cells in silicone oil in a 10-cm plane plate heated from below. From Koschmieder (1974). **b.** Faraday waves in silicone oil in a 32-cm circular container vibrating at a frequency of 20 Hz. From Kudrolli and Gollub (1996). **c.** Common human visual hallucination pattern calculated using coupled feedback in a two-layer artificial neural net. From Ermentrout and Cowan (1979). **d.** Cell self-assembly from molecular interactions in homogenized egg cytoplasm from African clawed frog, *Xenopus laevis*. From Cheng and Ferrell (2019)

cortex, on the order of 10 Hz (Henke et al., 2009). The energy source is the stored electrical potential within neurons.

- Cell self-assembly (Fig. 13d). Reported by Cheng and Ferrell (2019) in homogenized egg cytoplasm from African clawed frog. Newly formed cells are observed to form a hexagonal lattice. No genetic material is present. In the context of emergence, the formation of this pattern would be expected to arise from coupled feedback between molecular components of the cytoplasm. The energy source is adenosine triphosphate (ATP). Unlike previous examples, a stable physical structure is formed.
- Honeycomb formation. It has been mathematically proven (Hales, 2001) that a hexagonal lattice is optimal in terms of dividing a surface into regions of equal area with the least total perimeter, which explains why it was evolutionarily retained. However, a mathematical model for honeycomb formation has not yet been published. Emergence theory predicts that a honeycomb is a bifurcation-based emergent structure formed as a result of coupled feedback between worker bees.

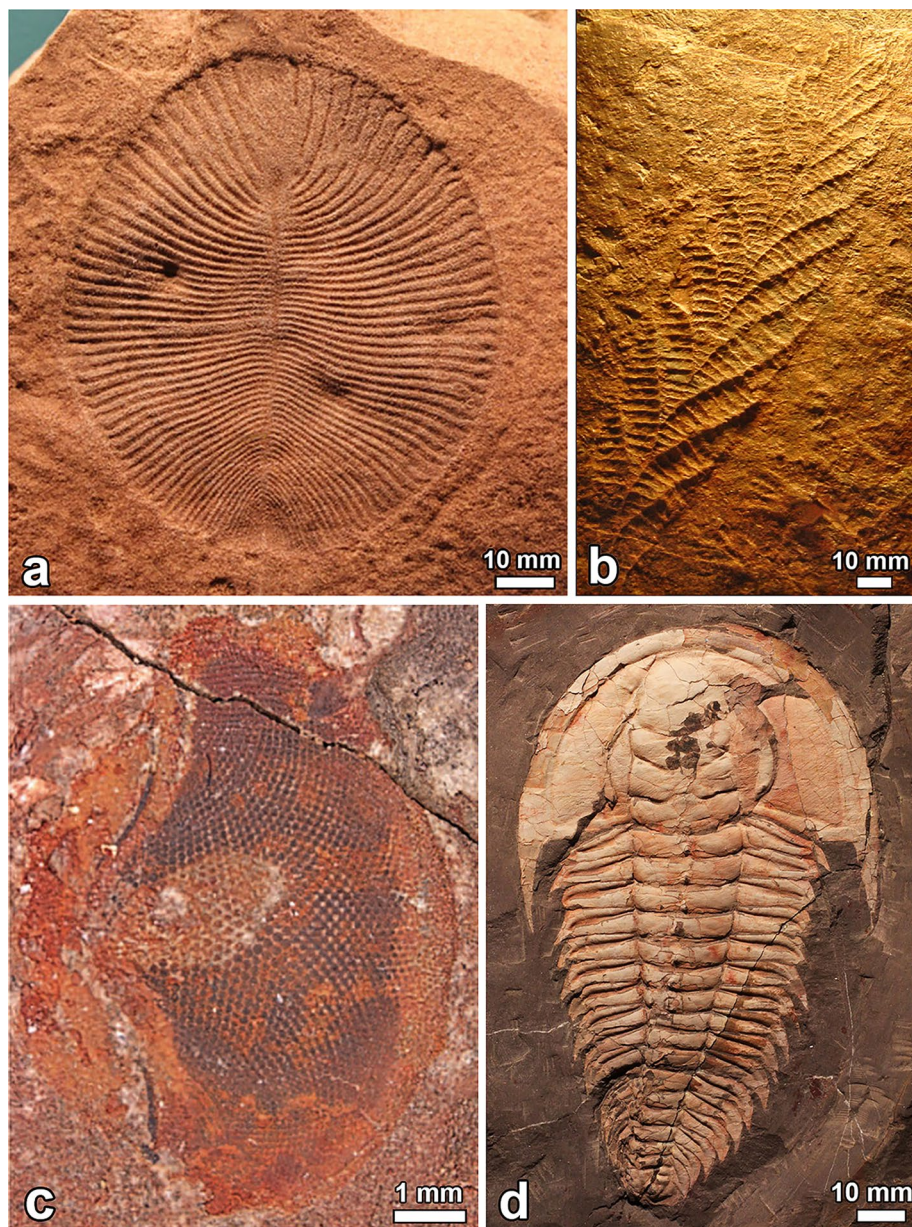




**Fig. 14** Turing patterns, morphogenesis. **a.** Examples of calculated Turing patterns. **b.** Mbu pufferfish (*Tetraodon mbu*) exhibiting a Turing pattern. **c.** Complex pattern around the eye of white-spotted pufferfish (*Arothron hispidus*, left) simulated using Turing pattern mechanisms (right). Modified from Turing (1952) and Kondo and Miura (2010)

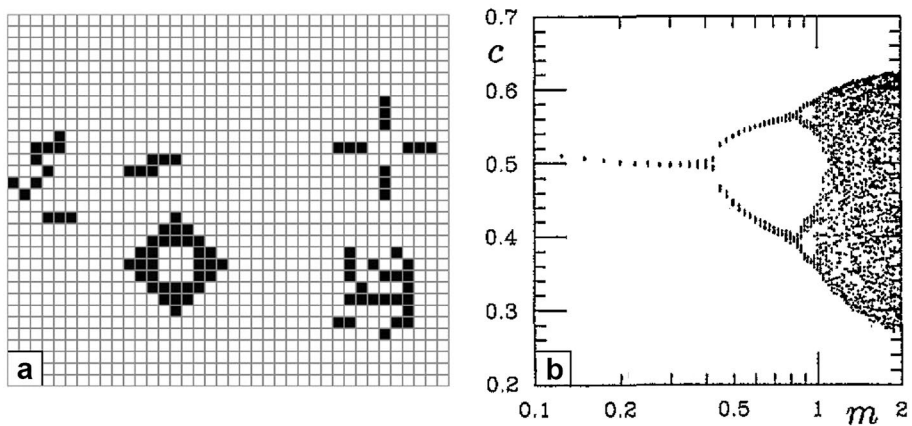
### Turing patterns

Turing (1952) proposed a theory of morphogenesis based on a dynamical system involving coupled-feedback reactions and diffusion in which bifurcation generates spatially nonuniform stationary solutions (e.g., Murray, 1990; Forgacs and Newman, 2005). It has been remarkably successful at reproducing patterns observed in animals (Fig. 14) and continues to be the leading explanation for how genes (and the proteins they encode) produce observed morphologies (e.g., Murray, 1990; Tompkins et al., 2014). The core of the Turing (1952) morphogenesis theory shares a number of similarities with the later-discovered BZ reaction in that the components form a coupled feedback system that produces ordered patterns using a mechanism based on bifurcation and deterministic chaos (e.g., Rössler, 1976; Tompkins et al., 2014).



**Fig. 15** Multicellular emergence as a possible cause of Cambrian explosion. **a.** Late Ediacaran fossil of genus *Dickinsonia*. From Hoekzema et al. (2017). **b.** Late Ediacaran fossil of genus *Charnia*. From Hoekzema (2015). **c.** Early Cambrian fossil arthropod eye with hexagonal pattern typical for emergent structures. From Lee et al. (2011). **d.** Early Cambrian fossil trilobite *Redlichia rex*. From Holmes et al. (2019)





**Fig. 16** Self-organization of cellular automata. **a.** Example of patterns produced by the Game of Life after 100 steps (generations) starting from a random array of equally likely 0s and 1s of size  $10 \times 15$ . From Zenil (2015). **b.** Bifurcation diagram for a Game of Life type cellular automata network.  $m$  is a ‘mixing parameter’ determining the distance a cell is allowed to move each iteration, and  $c$  is relative density of non-zero cells. From Boccaro et al. 1994

## Cambrian Explosion

Arguably one of the most significant weaknesses in the theory of evolution is the so-called ‘Darwin’s dilemma’, ‘the manner in which species belonging to several of the main divisions of the animal kingdom suddenly appear in the lowest known [Cambrian-age] fossiliferous rocks’ (Darwin, 1859). This was later termed the ‘Cambrian explosion’, referring to the sudden appearance of nearly all major animal phyla in a geologically short time period between 542 and 520 million years ago (e.g., Zhuravlev and Riding, 2001), the cause of which is not well understood (e.g., Marshall, 2006). The roots of the Cambrian explosion extend ~30 million years earlier to the period termed the Avalon explosion (Shen et al., 2008; Xiao and Laflamme, 2009) in the Late Ediacaran period, referring to the appearance and proliferation of new types of animals exhibiting simple geometric organization and bilateral symmetry. Perhaps the earliest of these is the genus *Dickinsonia* (e.g., Bobrovskiy et al., 2018).

The appearance of *Dickinsonia* (Fig. 15a) may be explained by bifurcation-based emergence on multicellular level. Although multicellular animals (metazoans) such as *Otavia antiqua* appeared significantly earlier in the fossil record, between 720 and 660 million years ago (e.g., Valentine, 2002), these earlier organisms were morphologically amorphous. *Dickinsonia*, in contrast, consists of segments that increase in number as the organism grows. The geometric regularity of *Dickinsonia* can be explained by a growth model (e.g., Hoekzema, 2015; 2017) incorporating a mechanism similar to the BZ reaction, oscillating between two states as the organism grows, resulting in a regular pattern of segments.

Another common animal fossil, of genus *Charnia* (Fig. 15b), also appeared in the Late Ediacaran and repeats this pattern, but in addition to primary alternating segments there are secondary segments, approximately equally spaced, perpendicular to primary segments. This self-similarity gives it a fractal order of two (Hoekzema, 2015).

The beginning of the Cambrian period is marked by a significant increase in morphological diversity built on repeating geometric patterns. One of these is the hexagonal

lattice, a common bifurcation-based emergent structure discussed earlier, observed in the fossilized eye from the early Cambrian (Fig. 15c).

This evidence suggests that a possible cause of the Cambrian explosion was emergence, or life evolving the ability to self-organize on the multicellular level using order obtained from bifurcation and deterministic chaos. This self-organization resulted in a rapid rise in complexity (e.g., Sepkoski, 1979), as illustrated by the complex geometry of trilobites (Fig. 15d) from the early Cambrian.

## Cellular automata

The computational essence of emergence implies that it can be generated with computers, and indeed, this is the case. An example is cellular automata, such as the Game of Life (Conway, 1970; Gardner, 1970), which produce complex ordered patterns, and even organized systems, from arbitrary initial conditions and simple rules. The rules set up a system of coupled positive and negative feedbacks, and are iterated, fulfilling the requirements for emergence to occur and leading to observed bifurcation and deterministic chaos (e.g., Wolfram, 1984; Nowak and May, 1992; Boccara et al., 1994). Figure 16 shows self-organization of cellular automata from disordered (high entropy) initial states into ordered (low entropy) geometric patterns. Like the BZ reaction, cellular automata can be used to implement basic logical operations (e.g., Rennard, 2002), and, taking it a step further, construct a virtual universal Turing machine (e.g., Rendell, 2002) capable of performing any computer operation (Turing, 1936), illustrating how iterative application of simple rules involving coupled feedback can create extremely complex systems.

## Definition of life

As discussed in the main body of the paper, life has been difficult to define precisely. Based on the concept of emergence, we propose the following definition: *Life is a self-organizing, self-regulating entropy-maximizing iterator composed of a hierarchy of stable dissipative structures*. ‘Self-organizing’ refers to retrieving order from bifurcation and deterministic chaos via ‘self-regulating’ coupled feedback, ‘iterator’ refers to feedback cycles, or iterations, ‘entropy maximization’ and ‘dissipative structures’ grounds the definition in well-established thermodynamic concepts, ‘hierarchy’ refers to lower-order building blocks producing higher-order building blocks, and ‘stable’ means that continuous external energy input is not required. This definition applies to the simplest organisms, composed of, at a minimum, spontaneously folded macromolecules (proteins (e.g., Böhm, 1991) and nucleic acids (e.g., Coleman et al., 2000)) and self-organized lipid bilayer membranes (e.g., Cheng and Ferrell, 2019), as well as complex organisms that also exhibit emergence on multicellular and multi-organism (e.g., bird flocks, fish schools, insect colonies, etc.) levels. It excludes common counter-examples, such as fire, storm systems, convective systems, and crystal growth.

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**Authors' Contributions** K.L.B. conceived the original idea, produced the conceptual framework, and outlined the theoretical flow. S.J.M. encouraged O.A. and K.L.B. to investigate definitions of life from mechanistic and informational aspects, and supervised the project. O.A. designed the computational framework and wrote the manuscript with input from K.L.B. and S.J.M. All authors discussed the interpretation of results and contributed to the final manuscript.

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**Data Availability** Data was obtained from a public blockchain and is by definition available and immutable.

**Code Availability** All source code needed to replicate our results is provided in the Supplementary Information and will be uploaded to Github.

## Declarations

**Conflicts of Interest** Authors declare no conflicts of interest or competing interests.

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