The Thermodynamic Considerations of Evolution; the Role of Entropy in Biological Complexity

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Abstract

Darwin's theory of biological evolution became a cornerstone of modern biology. However, predictable fluctuations in entropy, genetic diversity, population number, and resource availability in ecosystems turn evolution into a cyclic process. Moreover, ecosystems are closed systems that only exchange energy and information with the outside, therefore, can be analyzed via thermodynamic principles. The sun's energy input drives the reversed Carnot cycle's four distinct phases. The first phase is a low entropy, fast-changing environment, spurring phenotypic plasticity. In phase 2, the population growth increases entropy, forming nutrient cycles via symbiotic, parasitic, predator-prey, and other interdependent relationships. In phase 3, the overpopulated, stressed ecosystem tests its boundaries via competitive and chaotic interactions that spread genetic innovations. Finally, in phase 4, extinction purges the non-evolvable genomes, but the surviving species carry the cycle's genetic innovations and make renewal possible. Therefore, compression and expansion of the ecospace by energy fluxes (i.e., ecosystem dynamics) are potent drivers of change. We propose a new law to explain how the sun's energy input leads to the cyclic increase of genetic complexity. The second law of intellect shows that genetic complexity never decreases but increases or remains constant.

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Definitions used in the text

Social or psychological temperature: Temperature indexes internal energy, and social or psychological temperature measures arousal or conflict (Escobar et al., 2021; O'Neill & Schoth, 2022: Deli and Kisvarday, 2020; Deli et al., 2021).

Therefore, individual organisms are analogous to particles, and their individual histories (even in complex organisms) are analogous to thermal fluctuations. For example, the focus is stable at low arousal, but information overload or stress causes an erratic oscillation across multiple subjects, resulting in aggravation, aggression, and risky behavior. In addition, the environment has an essential role because effective population size and supply abundance determines the nature of the interaction, therefore, arousal (Deli et al., 2021; Sella and Hirsh, 2005). For example, abundance allows low social temperature, such as cooperation and generosity (Tkadlec et al., 2020), but supply shortage causes competition (Crokidakis, 2017). At a critical level, cooperation disappears, and high-frequency information transfer promotes deterministic actions forming a high social temperature (Stewart and Plotkin, 2012).

Temporal field: Fields associate each point in space with a specific physical quantity. For example, gravity is a vector field, ensuring spatial organizational stability. Likewise, the genetic material, social, cultural, and intellectual organizations represent temporal information fields (Deli 2015). As the genetic material accumulates, the species' organizational history, cultural traditions, religious beliefs, and scientific knowledge code humanity's mental richness.

Genetic complexity: Genetic complexity is the structure and properties of genotype-to-phenotype maps enabling the quantitative comparison of the relative complexities of genetic systems (Charlesworth, 2001; Thompson and Galitski, 2012).

Introduction

At every level of biology, cells, tissues, neurons, viruses, plants, and animals solve problems and achieve goals by flexibly navigating metabolic, physiological, genetic, cognitive, and behavioral needs. For example, the cell's biochemical flows and reactions can run both ways, yet life is about growth and development. Similarly, confusing and seemingly arbitrary interactions generate complexity-increasing macroevolution with periodicities on many spatial and temporal scales (Roberts & Mannion, 2019).

Thermodynamics can predict the behavior across all physical systems with an axiomatic approach and a minimum of assumptions. The second law of thermodynamics states that the total entropy of a system either increases or remains constant in any spontaneous process; it never decreases (reviewed by Boojari, 2020). The law has inspired the analysis of entropy (Lotka, 1922. a, b; Annila & Baverstock, 2014; Pross & Pascal, 2017; Sherwin, 2018; Skene, 2020; Gladyshev, 2017) and thermodynamics in evolution (Ao, 2005 and 2008; Barton & Coe, 2009; Vopson, 2022).

The increasing complexity and organization during biological evolution, particularly the human brain's complex organization, is a blatant offense to the second law of thermodynamics. The most famous analogy is Maxwell's demon, a theoretical tool that can separate warmer particles from colder ones and illegally decrease system entropy. Maxwell's demon highlights the problem of decreasing entropy in biological systems. As a result, genomes' information entropy and the entropy of the organism appear to decrease, challenging the Darwinian concept (Vopson, 2022). For example, it cannot solve intelligent computations like the traveling salesman problem (Czégel et al., 2021).

Darwin recognized that all species share a common ancestor. In the generational change in heritable traits of biological populations, the fittest individuals are more likely to survive and create offspring (Darwin, 1859). However, irrational behavior can hasten the individual's demise or even the extinction of the species. According to the Darwinian theory of evolution, only natural selection determines which mutations are beneficial, and there is no deterministic correlation between any parameter and the probability that these mutations will occur. Nevertheless, genetic changes, such as the emergence of toeless lizards or humanity's switch to agriculture, have no selective advantage. Organisms often lose the functions of organs, yet evolution never proceeds toward the lesser organization. For example, whales have lost many functions during a macroevolutionary transition to the water (Werth, 2020), but they did not lose their mammalian complexity by turning into cold-blooded fish. For example, excessive reliance on the host causes anagenetic endoparasites' structure and physiological function simplification.

Biological systems utilize energy and materials from the environment for building tissues in an inherently systemic and dynamic process. Ubiquitous adaptive cycles reflect endogenously generated self-organization dynamics (Sundstrom & Allen, 2019). Higher levels influence and constrain the dynamics of lower levels in organizational hierarchies (Walker and Davies, 2012), allowing simple laws to give rise to a complex organization. How is life assembled? The problem of calculating the thermodynamic cost of the ecosystem by summing the chemical energy accumulated in the biological matter and the information conserved in the genetic material fails to account for the complexity. Life's molecular assembly encodes information and uses that information to determine the system's future state. According to Bennett, complex objects contain internal evidence of a nontrivial causal history (Bennett, 1986).

Furthermore, logical depth is intimately related to algorithmic complexity, the length of instructions needed to decompress a file in a context-dependent, causal manner. Therefore, a causal chain can represent a complex object. Likewise, assembly theory or causal set theory explains the emergence of life via complexity science; causal graphs explain relationships between the origins of objects.

Another difficulty is that evolution proceeds by long nearly-static periods punctuated by sudden "inventions" of novel phenotypic solutions on the macroevolutionary timescale. It is a multi-phase process with varying phase lengths (McMahon & Ivarsson, 2019) and periodicities (Roberts & Mannion, 2019). For example, cichlid diversification occurred by consecutive trait-specific pulses of morphospace expansion (Ronco et al., 2020). Although evolutionary processes are nonlinear, they show certain regularity of entropy and population number, which allows modeling by thermodynamics and statistical mechanics of equilibrium systems. In particular, the increase of disorder accompanying the increase of entropy can occur in microscopic degrees of freedom (e.g., thermal motion of molecules). At the same time, highly complex and organized structures emerge out of macroscopic degrees of freedom (Jeffery et al., 2019). Metastable states correspond to local minima of the free energy functional and can persist on different time scales. An information-theoretic description, for instance, is the mutual information between various macroscopic observables (Jeffery et al., 2019).

In sufficiently large populations, individual organisms are analogous to particles, and their histories are analogous to thermal fluctuations, resulting in predictable collective effects. Therefore, the maximum entropy principle, according to which the distribution of any quantity in a large ensemble of entities tends to the highest entropy distribution subject to the relevant constraints, can conceptualize relationships in biology, chemistry, economy, and consciousness science (Deli & Kisvarday, 2020; Deli et al., 2021; Fry, 2017; Jiang et al., 2016; Klimek et al., 2019) and even evolution (Frank, 2009; Frank and Smith, 2011; Vanchurin et al., 2021). The system's statistical tendency to increase entropy creates an entropic force. We speculate that the environment's entropic force pushes life toward the more efficient use of entropy, inadvertently increasing life's complexity and intellect ((Jeffery et al., 2019: Schrödinger, 1945).

Evolution transforms the sun's continuous energy input into a stepwise increase in genetic complexity. Each evolutionary cycle can be divided into well-separable phases characterized by predictable entropy, population number, resource availability, and genetic diversity. First, extinction bottlenecks compress the ecosystem's genetic potential while conserving entropy. Low entropy populations (phase first) accelerate the order and complexity of the genetic material. However, horizontal gene transfer spreads genetic elements in high-entropy ecosystems, allowing selection to play a crucial role.

Considerations of Entropy

Photosynthesis, the dominant energy source in most ecosystems, converts light to C-H bonds in organic material, serving cell complexity, movement, and intellect. Therefore, endothermic processes, such as biological organization, depend on exothermic operations (Ménendez, 2021; Ramstead et al., 2018). Moreover, biological systems accumulate energy in the genetic material, which forms a stable field unaffected by the chaotic environment. Compartmentation also applies to metabolites and the reductions in entropy from metabolic equilibrium (Sabater, 2022). Landauer's principle shows that information storage is analogous to a temperature decrease or "phase transition." Thus, the genetic material, which acts as a field, separate from the system (Figure 1), represents Maxwell's demon.

The role of entropy in evolution is a particularly sought-after problem (Bartlet, 2017; Cohen & Marron, 2020; Kondepudi et al., 2020; Pross & Pascal, 2017; Sherwin, 2018; Skene, 2015; Roach et al., 2020; Roach, 2020; Torday, 2021; Wong, 2020). Entropy measures the variety of existing possible configurations within a system.

$$S = -k_B \sum_i p_i \log p_i$$

where S is the entropy, $k_B$is the Boltzmann constant and p_i is the current state of the system.

Because entropy production directs all changes toward equilibrium, it is connected to time's arrow (Andrieux et al., 2007; Gaspard, 2005; Roldán and Parrondo, 2010). Therefore, time can be defined as the entropy generation rate (Kostic, 2014). Free energy (von Helmholtz, 1882) defines the maximum amount of work a thermodynamic process on a constant volume can perform. For example, organisms require materials from the environment for generating energy and building tissues; energy fluxes (i.e., ecosystem dynamics) can drive complexity (Bush & Pruss, 2013).

An entropic force, derived by Neumann, is an emergent phenomenon resulting from the tendency of a thermodynamic system to maximize its entropy via Brownian motion. In an ecosystem, the species distribution in an ecological niche follows a Brownian distribution.

$$F(X_0) = T \nabla_x S(X)|_{X_0} \qquad (1)$$

where T is the temperature, S(X) is the entropy associated with the macrostate X and X_0 is the present macrostate.

Genetic diversity corresponds to the number of microstates (Boltzmann entropy) (Sailer & Harms, 2017). The entropic force enhances the number of microstates in the ecosystem. Then, at a critical state, it precipitates extinction, with the sharp reduction of entropy and genetic diversity. Because only the genes are transmissible across generations, genetic information represents an independent medium (i.e., field). Therefore, the thermodynamic changes and the devastation of extinction preserve the cycle's genetic innovations. Therefore, the cycle can repeat with the same state variables of entropy, genetic diversity, social temperature, and resource density, turning evolution into a forced, complexity-increasing harmonic motion (Table I). Therefore, evolution is driven by the entropy generation of the physical world (Schrödinger, 1945; Jeffery et al., 2019).

At equilibrium, mutations often remain silent (the genetic acceleration is zero); the dynamical ecosystem does not generate evolutionary changes. However, a non-equilibrium bias towards maximum instantaneous entropy production moves the ecosystem toward higher-entropy macroscopic states. Therefore, mutation frequency shows an initial decrease during eras with low genetic concentration and subsequently changes parallel with the population number (Vahdati et al., 2017). The genetic (i.e., field) modifications are significant in the low entropy phase, but the population number is low. In contrast, in the high entropy phase, the genetic changes are minor, but the population density is high. Therefore, notable evolutionary changes are increasingly likely at the cycle's low and high entropy sections.

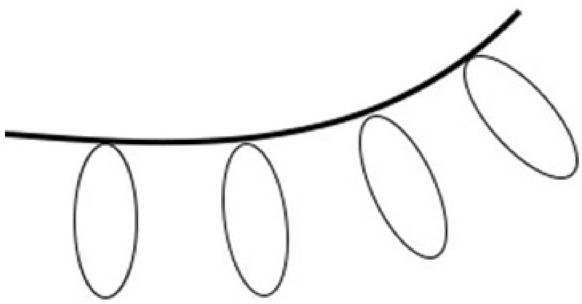

Figure 1. The thermodynamic origin of genetic complexity as a field The thermodynamic cycle (indicated by an oval) represents a fluid, chaotic and reversible process. The energy field (solid line) represents the increasing complexity of the genetic material.

Table I. Comparison of the evolutionary cycle and genome representing an orthogonal field

The evolutionary cycle	The genome as an orthogonal field
The cycle can be divided into well-defined entropy, social temperature, and resource density phases.	The genome represents stable and unique energy (complexity).
The cycle's phases are chaotic, noisy, and often reversible.	The complexity field satisfies the second law of intellect.
The cycle forms a discrete loop; therefore, it must end.	The cycle's innovations become an indelible part of a heritable material.

The Carnot Cycle as an Evolutionary Model

The Carnot cycle is a closed thermodynamic cycle; therefore, it can only exchange energy with its environment. Further, it is an idealized theoretical process between two heat reservoirs with vanishing net entropy production, where the phases repeat precisely. The macroscopic variables, such as temperature, pressure, and volume, are quantifiable characteristics without details on individual molecule dynamics. For example, the temperature manifests particles' kinetic energy, but the social temperature is the fierceness of competition, driven mainly by hunger and lack of living space (Deli et al., 2021). Anxiety and aggravation represent significant energy requirements in emotional animals (Gao et al., 2022; Saarimäki et al., 2017), but stress causes aberrant, erratic behavior in all animals, plants, and living things.

The Earth receives solar radiation from the sun, causing an energy influx, the difference between absorbed and emitted radiation. The ecosystem consists of all solid ground, water, and air, which theoretically can satisfy the ecosystem's nutrient needs. This way, the ecosystem is a closed system where the sun's energy input sets the limit of achievable computational efficiency (biological complexity gain) during the cycle. Moreover, genetic complexity resists extinction; therefore, it is a conserved quantity (Thompson and Galitski, 2012). Although the gene pool's intergenerational stability ensures the species' constancy, it manifests the organism's evolutionary history and represents a potential for its future.

We must note another crucial element here. A constant stimulus can produce fluctuating parameter outcomes, such as self-organized criticality. For example, in the famous "sandpile experiment" (Lang and Shkolnikov, 2019), a slowly building conical sandpile triggers an avalanche of sand in a completely unpredictable fashion. Likewise, mass extinctions act as avalanches, which turn the sun's biomass generation periodic. According to recent studies, evolution consists of extended periods of stasis that accumulate mutations without producing significant phenotypic change, followed by rapid morphological jumps (Bakhtin et al., 2020; Katsnelson et al., 2019; Lowery & Fraass, 2019; Rosenberg, 2022). As a result, radiations and extinctions are decoupled in time (Cuthill et al., 2020; Fan et al., 2020; Lynch et al., 2016), and genetic innovations precede Darwinian selection.

The fossil record testifies that the cycle of death and birth, extinction and origination, is a constant source of change and renewal in the living world (Babcock et al., 2015; Marshall, 2017). Major extinctions cause the vanishing of specific taxa but spare species with adaptive evolution capacity (Bush et al., 1977; Wagner, 2020). Therefore, extinction events are crucial in the increasing complexity transformation of the ecosystem (Boggs & Gross, 2021; Parry, 2021). Furthermore, extinction events section the geologic time into eons, eras, and periods, with specific genetic and morphological features

(Figure 2; notice the similarities to Figure 1). Therefore, both shorter and longer cycles terminate in extinctions.

Capricious evolution trajectories enhance the probability of either extinction or innovation because the demise of less evolvable genomes allows flexible genomes to survive. These "survivor" genomes carry the genetic and morphological innovations of the cycle. Therefore, extinction events accelerate evolution because genetic streamlining formulates a radically new and more complex biosphere (Lehman & Miikkulainen, 2015). In the rapid expansion through vacated niches, the genotype-phenotype maps determine the long-term evolutionary trends (Ahnert, 2017).

The entropic force pushes entropy into biological systems and ultimately accumulates complexity in the genetic material, an "invisible" factor in the ecosystem's structural relationships (Figure 1). Gravity, the most fundamental field, underlines all of space, but information fields are temporal. For example, genetic information directs the cell's organization and life's progression. Therefore, in contrast to gravity, temporal fields represent a gradation of complexity. Moreover, the complexity must either remain the same or increase in the limit of a reversible process (Vopson, 2022; Vopson & Lepadatu, 2022). The temporal field's resistance to complexity loss leads to a tendency for energy accumulation, the second law of intellect (Figure 3). Because the second law of thermodynamics states that the total entropy can only increase over time for an isolated system, it points to the existence of an entropic drive. Intelligent systems can take advantage of the entropic drive to increase complexity. The second law of intellect explains organisms' increasingly efficient use of entropy via an upward complexity spiral. Therefore, the environment's entropic drive can explain the complex facets of evolution and the evolutionary, technological, and social progress.

A healthy ecosystem depends on the equilibrium of nutrients, wastes, air, energy, and other resources (Table II). An ideal evolutionary cycle can be divided into four well-defined phases based on recurring state variables: entropy, species number, genetic diversity, and resource-richness (Crokidakis, 2017; Sundstrom & Allen, 2019; Wong, 2020). We model the ideal evolutionary cycle via the reversed Carnot cycle, which absorbs heat from the low-temperature reservoir and deposits it in the hot-temperature reservoir via an energy-requiring process (Figures 4, 5). The cycle starts with adiabatic compression (A-B). Then, heat is rejected during the reversible isothermal compression (B-C). Next, reversible Adiabatic expansion expands the ecosystem slowly until the social temperature drops to T1 (C-D). Finally, isothermal expansion absorbs heat (D-A). The following discussion will focus on animals, but plants form a similar evolutionary progression.

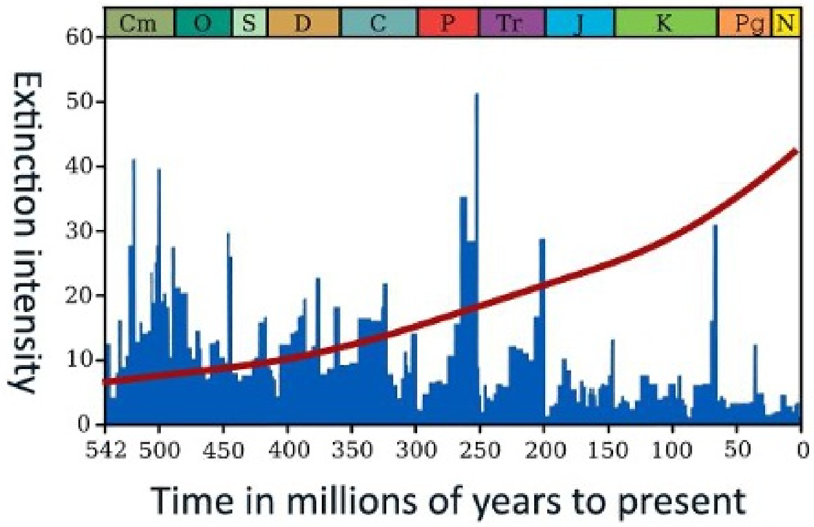

Figure 2. The field representation of complexity throughout evolution (Marine extinction intensity during the past five hundred million years). Over time, the increasing genetic complexity demonstrates an upward trend (red line). Resource: Wikipedia

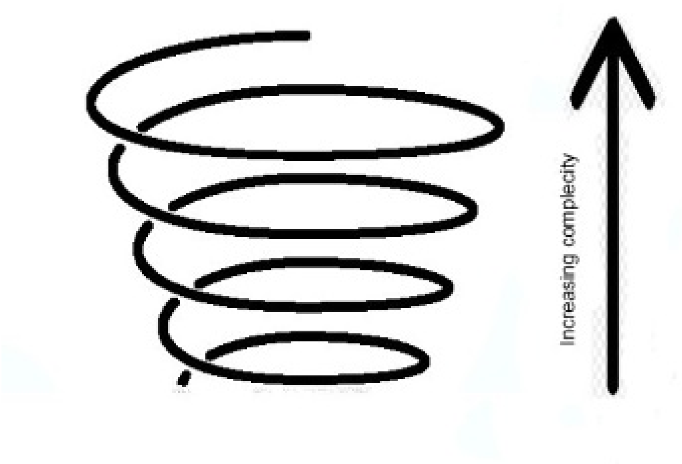

Figure 3. The hierarchic field structure Each period of the spring represents an evolutionary cycle.

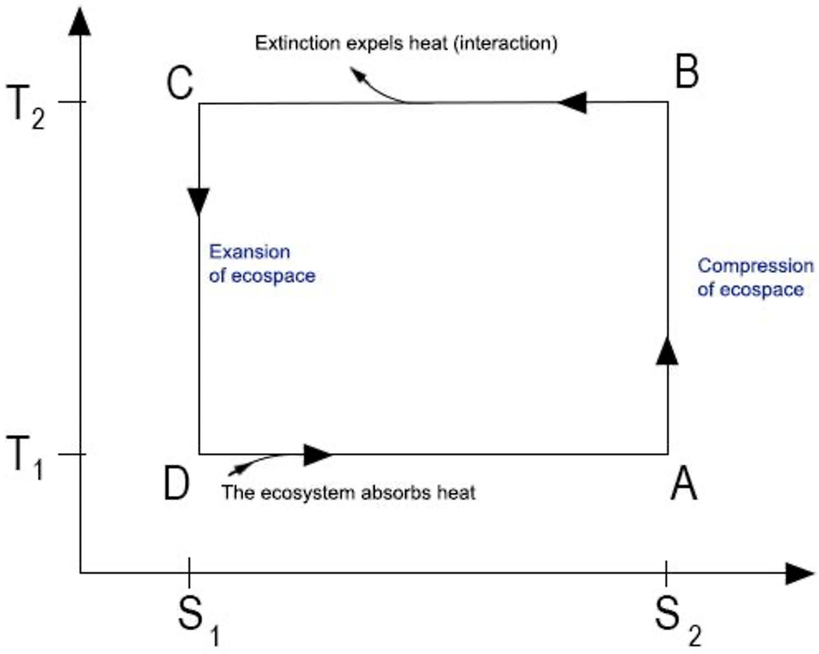

Figure 4. The reversed Carnot cycle representation of the evolutionary cycle The genetic and morphological complexity of the biosphere increases in discrete steps. (A-B) Overpopulation generates competition, increasing social temperature. (B-C) Extinction reduces genetic diversity and population (rejecting genetic material as heat). (C-D) The survivors occupy isolated pockets of the segregated environment. (D-A) The sun's energy input increases the population and genetic variety (D-A).

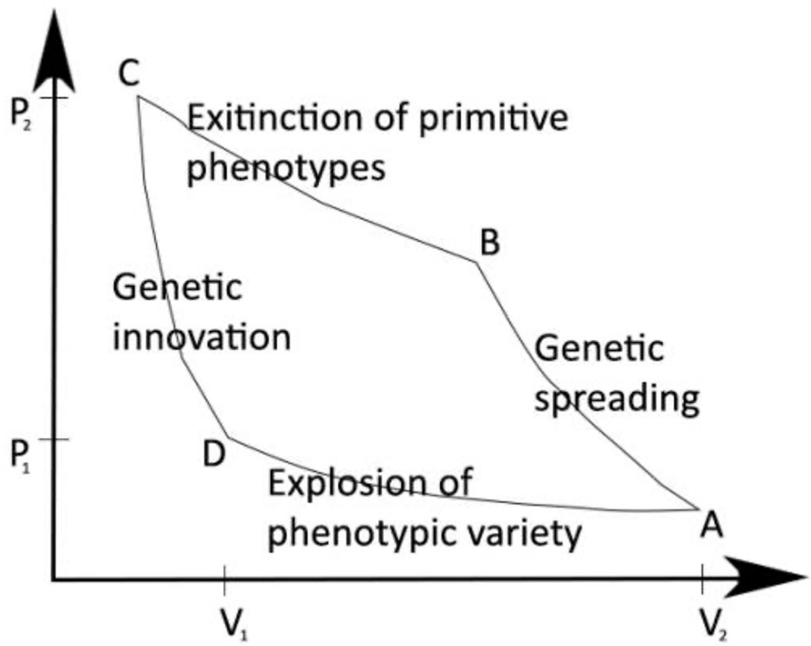

Figure 5. Phenotypic and genotypic changes shape the evolutionary phases In the first phase (C-D), low entropy spurs genetic ordering and complexity-increasing transformations. In the second phase (D-A), population expansion into diverse environments leads to phenotypic and genotypic variety explosion. The place within the food chain drives the diversification of the phenotype. In the third phase (A-B), stress and

social anxiety cause competition, spreading genetic elements in the ecosystem. Environmental degradation increases social pressure and temperature. In the fourth phase (B-C), extinction eliminates the non-evolvable genetic elements.

Table II. The characterization of a typical evolutionary cycle

	Phase One (A-B)	Phase Two (B-C)	Phase Three (A-B)	Phase Four (B-C)
Social temperature	↓ (Ecospace expansion decreases social temperature)	Low	↑ (Increasing with population expansion)	High
Population number	Low	↑ Population growth	High	↓ Extinction
Entropy	Low	↑ (Increasing)	High	↓ (Falls)
Evolutionary changes	Complexity, order	Perfection of the species	Specialization, small genetic changes	Survival of the fittest
Heat flow	Adiabatic	A growing population absorbs the sun's energy.	Adiabatic	Extinction, heat loss

Discussion of Evolutionary Phases

Phase 1 (C-D). Start of a New Cycle

The clear separation in the fossil record indicates that mass extinctions coincide with the destruction of the biosphere. Extinction comes for "free," acting as heat rejected by the system. Thus, by sealing the fate of evolutionary approaches that no longer work, extinction creates a "clean slate" (LaBar & Adami, 2016; Kirchner & Weil, 2000), where fast evolution can take place. In the first phase of evolution, resource abundance represents energy dominance (Figure 6), leading to three essential qualities that make renewal possible.

1, First, nature abhors a vacuum. Extinctions, acting as rejected heat, open a population vacuum in empty niches. Geographic isolation facilitates the evolution of co-adapted alleles at multiple physically unlinked loci (Waters and McCulloch, 2021). Newly mixed gene pools may enrich the adaptive genetic variation and allow for fast adaptation. When alleles involved in adaptation to alternative environments are present in high frequencies in the population, reassembling these ancient alleles can trigger a rapid and parallel ecological differentiation.

Although evolution depends on many factors, the availability of resources is one of the most critical environmental factors shaping developmental processes. In the late eighteen hundreds, Peter Kropotkin (1902) observed that biological richness inspires generosity and cooperation in ants, bees, falcons, and people (Connelly et al., 2017; Tkadlec et al., 2020). High resource density encourages maximizing individual power via experimentation, play, and organization. Cooperation positively affects reproduction and survival (Arlettaz et al., 2017; Katsnelson et al., 2018; Liao et al., 2019; Tkadlec et al., 2020; Wolf et al., 2018). In game theory, prisoner's dilemma studies support the above ideas (Lee et al., 2018). Generosity and play is the energetically most frugal behavior option, in contrast to high-energy conflict and competition.

2, Second, fast-changing environments spur evolution. The changing environment can trigger phenotypic plasticity (Boggs & Gross, 2021; Zhang et al., 2021). Over the past decades, evidence has shown surprisingly fast adaptation, such as re-using the same genes, in changing environments (Burtsev et al., 2022). Inversely, extreme phenotypic changes, speciation, or other evolutionary innovation require significant environmental changes, such as adaptations to a novel niche (Burtsev et al., 2022; Brun-Usan et al., 2021; Boggs & Gross, 2021; Pentz et al., 2020; Ng & Kinjo, 2022; Zhang et al., 2021). Furthermore, evolutionary innovations generate rapid expansion (Lehman & Miikkulainen, 2015; Nevo & Beiles, 2011); adaptive plasticity improves survival in changing environments by improving organizational function, such as the Ediacaran increase of diversity (635 to ca 580–550 yr) (Knoll et al., 2006). Computer studies also support a plasticity-led evolution (Ng & Kinjo, 2022; Levis & Pfennig, 2019a, b; Burtsev et al., 2022; Brun-Usan et al., 2021; Rago et al., 2018).

Underlying trait architectures and demographic characteristics of natural populations can constrain adaptation through different mechanisms. For example, exaptation in complex organisms, the recruitment of junk DNA, and widespread mobile element presence can generate complexity (Lynch and Conery, 2003). In addition, mobile elements can shift the function of a trait, dramatically increasing evolutionary potential (Koonin, 2016). For example, SARS-CoV-2 structural proteins changed substantially in the initial months and stabilized later as the virus adapted to the global human population (Ghanchi et al., 2021; Santoni et al., 2021).

3, Third, genetic diversity corresponds to the number of microstates (Boltzmann entropy) (Sailer & Harms, 2017). The highly chaotic environment forms a "liquid phase," which dictates low degrees of freedom for the organisms. In phase 1, the low genetic diversity population represents low entropy when order-increasing genetic changes coalesce into new functions and utilities (Andersson et al., 2015; Kondepudi et al., 2020; Xia et al., 2020) (Table I). Selfish genetic elements and gene duplication due to errors in DNA replication and repair machinery significantly increase evolvability (Jouffrey et al., 2021). Preexisting genetic variation can spur rapid and often parallel ecological adaptation. For example, gene duplication serves as degeneracy in the evolution of new functions (reviewed by Magadum et al., 2013) and other complexities (Katsnelson et al., 2019). Conversely, preexisting molecular architecture can converge toward functional utility or new organisms and species by reorganizing genetic material, such as parts of the nervous or muscle system (Morris, 2010).

When multiple populations colonize seemingly similar habitats, they may evolve similar genes, traits, or functions. Evidence shows a rapid evolution of complex behavior, such as the parallel evolution of emotions and thermoregulation (Soslau, 2019), in birds and mammals (Burtsev et al., 2022). The two species evolve the same traits in the same (Marques et al., 20222) or different environments.

The two-step process of initial divergence in an ancient and potentially isolated population and subsequent admixture putatively also applies to other examples of fast and repeated ecological divergence. Repeated ecological divergence at the same loci occurs in some iconic examples of parallel evolution, such as stickleback, cichlid fishes, and Heliconius butterflies (Van Belleghem et al., 2018). Convergence might generate repetitive evolution among species, depending on gene flow among populations and the phylogenetic relatedness of the lineages involved (Waters and McCulloch, 2021).

Parallel and convergent evolution suggests that evolution is not an accidental series of events but a constant search for opportunities to increase complexity.

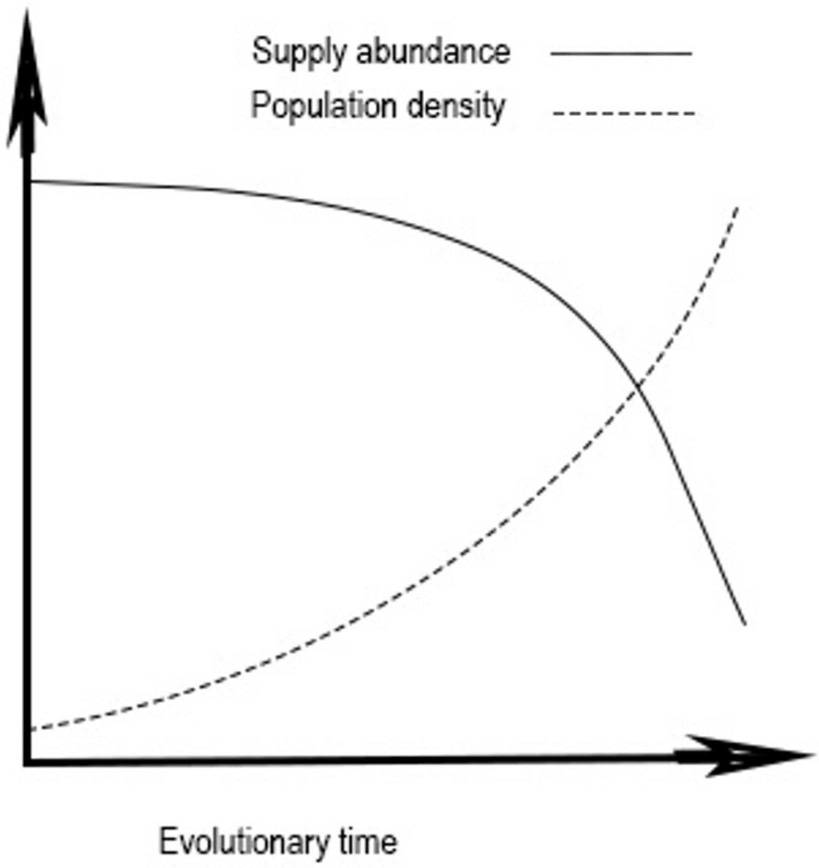

Figure 6. Supply availability in the ecosystem as the function of population density during an ideal evolutionary cycle

Phase 2 (D-A). Expansion

The Second phase of the evolutionary cycle forms an equilibrium position. Low social temperatures allow a close interdependence between the nutrient supply and the demands of the ecosystem. Environmental resources and the sun's heat input engender rapid population growth and diversity, which correlates to microstates in physics. For example, laboratory studies produced aggregate multicellularity (Márquez-Zacarías et al., 2021; Pentz et al., 2020), but organizational changes required genetic intervention (Daane et al., 2021).

The growing ecosystem's regular and organized interactions gradually fill the ecological niches. The highly structured processing and recycling of nutrients, wastes, air, energy, and other resources between producers and users give rise to food chains (Kingsbury & Hong, 2020), forming the backbone of the ecosystem. Symbioses and predator-prey cycles form equilibrium points with perfect interdependence, dynamic stability, and fitness (Good et al., 2017; Koonin, 2016; Vahdati et al., 2017). Populations of predators and their prey usually follow predictable cycles, which designate the species' place within the ecosystem.

The species must adapt to a new environment or perish. The meaningful mutation steps from the origin (p) form the system's state and increase the number of microstates. With the increasing entropy, we lose information about the system's initial state, making it challenging to retrace the exact evolutionary path. The Kullback-Leibler divergence can express the genetic distance between the current algorithm (p) and the expected (final) output (q). A species (p) can adapt to a new environment by evolving into (q).

$p(x) \geq 0$, $q(x) > 0$ = probability distribution of species x, where

$p(x)$ = probability distribution of species x at time 0,

$q(x)$ = probability distribution of species x at equilibrium.

$$D_{KL}((p(x) \| q(x)) = \sum_{x \in X} p(x) \ln \frac{p(x)}{q(x)} \geq 0 \qquad (1)$$

where $\ln \frac{p(x)}{q(x)}$ quantifies change. Genetic updating depends on $D_{KL}(px \| qx) \geq 0$ and disappears when q = p.

S is the entropy, and T is the social temperature for an isolated system, $dS = \frac{\delta Q}{T}$. The solar energy input nurtures endothermic processes, in which free energy moves the system toward high entropy equilibrium.

The population number P_i changes as a function of its fitness.

$$\frac{dP_i}{dt} = F_i p_i \qquad (2)$$

where F_i is the fitness of population p_i

The prospect of the ith species is given by the difference in the fitness of the i-th type and the mean population fitness.

$$\frac{dP_i}{dt} = \left(F_i - < \mathrm{F} > \right) p_i \qquad (3)$$

where <F> is the mean fitness at equilibrium.

The system's state has been formed by the meaningful mutation steps from the origin (p) and the factor for the increase in the number of microstates (divergence).

Phase 3 (A-B). Overpopulation

Biological systems are messy, but excessive details leave higher-level organizations stable. Noise generates diversity; chaotic environmental and chemical changes, such as error-prone polymerases, provoke transient mechanisms for generating adaptive phenotypes (Ronco et al., 2020). Finally, entropic effects push cryptic (hidden) variations into otherwise-inaccessible regions of the adaptive landscape (Vahdati et al., 2017; Zheng et al., 2019).

Microscopic fluctuations drive the system towards more probable states; horizontal gene transfer spreads the genetic elements (Rosenberg, 2022; Sakaue et al., 2017), dispersing potential for new functions and morphologies (Sailer & Harms, 2017) and species formation (Woods et al., 2020; Suh, 2021). Entropy increases with time (Cohen & Marron, 2020; Jennings et al., 2020), generating disorder, which has diffusional effects on gene spreading (LaBar & Adami, 2016; Sailer & Harms, 2017) without producing substantial evolutionary change. Therefore, entropic force represents microstate fluctuations of the gene pool, a trend that reverses the low entropy first phase.

The ecosystem has well-defined boundaries beyond which the population cannot expand. For example, fish cannot live on land; mountains or bodies of water confine land animals, while the range of their food source binds birds. Population growth causes a sharp decline in the availability of food and other resources (Figure 6). In Phase Three, the perfect equilibrium of Phase Two is upended by energy shortage. When the dwindling supplies reach a tipping point, defections sweep through the population, and generosity disappears (Gorban et al., 2021; Hoek et al., 2016; Kropotkin, 1902). Competition for resources increases the social temperature. High social temperature is less stable and more volatile, causing a sharp transition from cooperation to competition.

However, conflict and competition have high energy needs, degrading well-being, and social cohesions. Hierarchical interactions create winners and losers. Resource scarcity prompts stress, food fights, within-group scramble, and behavioral and other physiological effects (Gorban et al., 2021; Harris et al., 2010; Hoek et al., 2016). The degradation and environmental destruction of resources exhaust the ecosystem. In a complicated relationship between mutation frequency and population number (Cui & Yuan, 2020; Vahdati et al., 2017; McAvoy & Allen, 2020), competition creates stochastic patterns, giving rise to evolution's statistical and unpredictable nature (Sailer & Harms, 2017).

At the start of the period (T=0), the survivors have an equal opportunity at evolution as the system evolves through a Markov process. Over time, the distribution (x) reached the equilibrium position.

$$x_t \; x_{t=1} \; x_{t=2} \; x_{t=3} \cdots \qquad (5)$$

where x_t is the distribution at time T.

In a chaotic, stressed environment, evolutionary change is limited to arbitrary gene flow, with the ability to stabilize the species' genome. At high entropy and social temperature, the cycle's free energy is minimized and must end.

Phase 4 (B-C). Extinction

In the overstretched ecosystem, environmental stressors can disrupt predator-prey cycles, symbiotic relationships, and homeostatic mechanisms, exposing cryptic genetic variation and allowing natural selection to act (Nijhout et al., 2017). The species ideally suited for their environment, "ideal phenotype," and species with lower genetic diversity are most vulnerable to extinction (Boggs & Gross, 2021; Ørsted et al., 2019), and the two conditions often coexist. Therefore, mass extinctions affect only the most specialized (inflexible) genomes, reducing genetic diversity (the number of microstates). Inversely, survivors are non-ideal phenotypes living in the margins. For example, proto-mammals lived in the shadow of better-adopted dinosaurs.

Repeated environmental shocks can squeeze vulnerable organisms' ecological niches (Dakos et al., 2019), causing marked reductions in population size, preceding the purported geological "extinction" event (Chiarenza et al., 2019; Dakos et al., 2019). For example, the onset of the Siberian Traps and South China intensive volcanism may have diminished communities' ecological resilience and functions well before the end-Permian mass extinction (Shen et al., 2018). A single environmental disturbance could collapse the ecosystem because the species' fitness has declined for thousands of years (Boggs & Gross, 2021; Parry, 2021). Indeed, extinctions are generally connected to ecospace destruction (Lehman & Miikkulainen, 2015) and decoupled from mass radiations (Cuthill et al., 2020; Fan et al., 2020; Lynch et al., 2016). Supercomputer fossil record analysis can validate the different dynamics of extinctions and diversifications (Fan et al., 2020; Wagner, 2020).

While neutral mutations have no fitness effects, selection pressure enhances the likelihood of deleterious mutations (LaBar & Adami, 2017) and decreases the probability of fixation (Cui & Yuan, 2018). Therefore, mutations can weed out failed evolutionary experiments and find optimal genotypes. Furthermore, evolutionary selection of the fittest requires equilibrium entropy, which exists in phases three and four of the evolutionary cycle, and thus satisfies the classic Darwinian concept (Skene, 2020). Thus, detailed studies of the evolutionary phases might be a promising area of study (Tkadlec et al., 2019).

During the expansion of the ecosystem, it moves from state q to p, the peak of population growth. During Phases 1-3, the species best adapted to the ecosystem has better prospects, but the advantage disappears during dramatic environmental changes (Phase 4); the best-adapted species go extinct first.

Conclusions

We extended the Darwinian Theory by distinguishing order-increasing (low entropy) and disordered (high entropy) transformations in a more nuanced understanding of evolution. Biological evolution is characterized by the periodic extinction of species that cannot adapt to environmental changes. Extinctions separate evolutionary periods, which consist of four well-separable phases.

Extinction, which reduces the number of microstates, gives rise to the first phase of the evolutionary cycle. Considering organisms as particles, this limited degrees of freedom phase represents a "liquid phase.' Survival depends on closely following the possibilities provided by the environment. The particles' small kinetic energy leads to generosity and altruism, representing the least energy path. The latter boosts social coherence, a process in which the species' genetic makeup and morphology stabilize and adapt to its unique habitat.

Nevertheless, the increasing population numbers inspire competition. Mutations in larger populations (Phase Three) find optimal genotypes by weeding out the failed evolutionary experiments, while the genetic and morphological innovations remain part of the "survivor" genomes. Therefore, Darwinian concepts, such as random mutations and selection of the fittest, requires high entropy equilibrium.

The sun's energy influx operates a forced complexity-increasing harmonic motion through periodic entropy, population number, and resource density swings. The endothermic evolutionary cycle accumulates energy in the genetic, morphologic, and intellectual organization, indicating a physical relationship between intelligence and entropy maximization. Therefore, the second law of intellect is the temporal field's tendency to accumulate energy as complexity. Energy fluxes (i.e., ecosystem dynamics) that generate ecosystem compression and expansion drive extinction or evolutionary change and point toward the generalization of the Darwinian Theory. Evolution is the saga of increasing entropy efficiency.

Genetic information preserves the organism's evolutionary history, forcing a stable temporal field despite changing environmental conditions or occasional genome simplification. Nevertheless, the evolvable organization represents future adaptability. Although the details and implications of the model remain to be worked out and validated with empirical data, the temporal field structure represents a general evolutionary trend of an unending upward complexity spiral. The evolutionary stability of the current ecosystem supports the conclusion that low entropy conditions are necessary for significant evolutionary jumps. Computer simulations, such as supercomputer analysis of fossil records and long-term evolution studies, can verify its points.

Thermodynamic principles underlie systems' movement toward organization or disorder. For example, in freshly formed ecosystems, organisms adapt by fast evolution. However, in fully formed ecosystems, fierce competition and a thinning of resources weed out less flexible genomes. Computer modeling can verify the thermodynamic framework of biological evolution in an organizationally and functionally well-connected ecosystem.

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