Entropies and the Anthropocene crisis [*]

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July 29, 2020

Abstract

The contemporary Anthropocene crisis is frequently described as the rarefaction of resources or resources per capita. However, both energy and minerals correspond to fundamentally conserved quantities from a physical perspective. A specific concept is required to understand the rarefaction of these resources. This concept, entropy, pertains to the configurations of energy and matter and not just to their sheer amount.

However, the physical concept of entropy is insufficient to understand biological and social organizations. Biological phenomena display both historicity and more synchronic, systemic properties. The concept of anti-entropy stems from the combination of these aspects. We propose that many vulnerabilities of living entities to the changes of the Anthropocene pertain to anti-entropy. They correspond to the entropization of anti-entropy, that is, a loss of organization. They can also be the disruption of anti-entropy production, that is to say, the loss of the ability to produce functional novelties.

Keywords: entropy, anti-entropy, resources, organization, disruption, Anthropocene

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1 Introduction

Despite cases of denial, citizens and governments increasingly acknowledge the Anthropocene crisis. Nevertheless, this crisis requires further theoretical characterization. For example, in the second "warning to humanity", signed by more than 15000 scientists, the arguments are convincing but are limited to the rationality of physics. The authors exhibit quantities that are growing or shrinking exponentially (Ripple et al., 2017) and it stands to reason that such a trend cannot persist in a finite planet. This line of reasoning is commonplace in physics and shows that a change of dynamics is the only possibility. For example, the said quantities may reach a maximum or the whole system may collapse. However, is this line of reasoning sufficient to understand the Anthropocene crisis and respond adequately to it?

Several authors have specified the diagnosis of the Anthropocene crisis. They argue that this crisis is not a result of the Anthropos *sui generis*, but the result of specific modes of organization of current human societies. Let us mention the concept of capitalocene (Moore, 2016). In the concept of capitalocene, the dynamics of capital is the decisive organizational factor. The capital opened the possibility of indefinite accumulation abstracted from other material objects. Along a similar line, the concept of plantationocene posits that the plantation is the damaging paradigm of social organizations and relationships to other living beings (Haraway, 2015; Davis et al., 2019). In both cases, the focus is on human activities and the reason why they are destructive for their conditions of possibility. These accounts provide relevant insights but are insufficient in their articulation with natural sciences.

To rearticulate economics and natural processes, Georgescu-Roegen (1993) emphasized the theoretical role of entropy. Economists should part with the epistemology of classical mechanics where conservation principles and determinism dominate. In thermodynamics, the degradation of energy is a key concept, that is, the irreversible increase of entropy. Methodologically, the implication is that economists should take into account the relevant knowledge about natural phenomena instead of working on self-contained mathematical models.

This work has been reinterpreted by Stiegler (2018). B. Stiegler argues that the hallmark of the Anthropocene is the growth of relevant entropies at several levels of analysis, including at the level of social activities. In this paper, we will discuss several aspects of this idea with a focus on mathematized situations or situations where mathematization is within sight.

We first explain why entropy is a critical concept to understand the "consumption" of energy resources. We provide a conceptual introduction to the thermodynamic concept of entropy that frames these processes in physics. Similarly, we will discuss resources such as metals and argue that the property impacted by biological and human activity

is not their amount on Earth but their configuration. Concentrations of metals increase when geological processes generate ore deposits. On the opposite, the use of artifacts can disperse their constituents. Last, compounds dispersed in the environment can be concentrated again by biological activities, leading to the contamination of marine life with heavy metals, for example.

To address biological organizations and their disruptions, we first develop several theoretical concepts. The epistemological framework of theoretical biology differs radically from equilibrium thermodynamics. We introduce the concepts of anti-entropy and anti-entropy production that mark a specific departure from thermodynamic equilibrium. We show that they enable us to understand critical destructive processes for biological and human organizations.

2   Entropy in physics and application to available resources

In this section, we will discuss two kinds of resources relevant to the economy and show that the proper understanding of these resources requires the concept of entropy in the physical sense of the word. The first case that we will discuss is energy, and the second is elements such as metals.

2.1   Energy and entropy

The stock of energy resources is commonly discussed in economics and the public debate. However, it is a fundamental principle of physics that energy is conserved. It is a physical impossibility to consume energy *stricto sensu*. For example, a falling ball is transferring potential energy into kinetic energy, and if it bounces without friction, it will reach the initial height again, transforming kinetic energy back into potential energy. This remark is made repeatedly by physicists and philosophers but does not genuinely influence public discourses (Mosseri and Catherine, 2013). Georgescu-Roegen (1993) and authors who built on his work are an exception.

To dramatize the importance of this theoretical difficulty, let us mention that the increase in the temperature of a body implies the increase of its internal energy. Heat engines, including thermic powerplants, are a practical example of this: they transform heat into useful work (useful motion). We are then compelled to ask an unexpected question. Why would climate change and the subsequent increases in temperature not solve energy crises?

2.1.1   Thermodynamic entropy

The greenhouse effect keeps the energy coming from the sun on Earth, and at the same time, the shrink of resources such as oil leads to a possible energy crisis. The main answer to this paradox is that not all forms of energy are equivalent.

Let us picture ourselves in an environment at a uniform temperature. In this situation, there is abundant thermic energy environing us, but there is no means to generate macroscopic motions from this energy. We need bodies at different temperatures to produce macroscopic motions. For example, warming up a gas leads to its expansion and can push a piston. If the gas is already warm, it cannot exert a force on the said piston. It is the *warming* up of the gas that generates useful work, and this process requires objects with different temperatures.

An engine requires a warm and a cold source to sustain a temperature difference. This rationale led to design cycles where, for example, a substance is warmed up and

cooled down iteratively. These cycles are the basis of heat engines. XIXth century physicists, in particular, Carnot and Clausius, theorized these cycles. When generating macroscopic motion out of thermic energy, the maximum efficiency of the engine is limited.[1] The efficiency depends on the ratio of temperatures of the cold and the warm sources. When the temperatures tend to become equal, the efficiency decreases and tends to zero. Physicists introduced entropy to theorize heat engines' efficiency. As a side note, nuclear powerplants use the same principle, where the warm source is atomic fission, and the cold source is a river or the sea.

Now, let us consider that we have warm water and cold water and that we pour them together in a pot. After some time, the water will reach a uniform temperature, and we have lost the chance to extract mechanical work out of the initial temperature difference. This phenomenon is remarkable because it displays a temporal direction: we have lost the ability to do something. Theoretically, this kind of phenomena defines a time arrow that classical mechanics lacks.[2] Likewise, it is possible to generate heat out of mechanical work by friction, including in the case of electric heaters, but, as we have seen, the opposite requires two heat sources at different temperature.

Energy is a conservative quantity following the first principle of thermodynamics. The only way to remove energy from a system is to put it outside of the system. Being conservative should not be confused with being conserved. The energy of a system is not necessarily conserved; it can decrease if it is released outside, or increase if some energy comes from outside.

In this context, what is entropy? The classical thermodynamic perspective defines entropy as a quantity describing the state of a system together with other quantities like energy, volume, . . . Physicists used to think of heat as the exchange of an abstract fluid, the "caloric"; however, the possibility of a complete transformation of work into heat and the partial conversion of heat into work is not amenable to the definition of such a fluid. Nevertheless, the notion of fluid remains partially relevant to understand what entropy abstractly is. Entropy is proportional to the size of a system, like the mass or energy. Entropy can be exchanged, and in special situations called reversible, entropy is conservative, like energy.

However, the difference between entropy and energy is that entropy tends to increase towards a maximum in an isolated system, following the second principle of thermodynamics. This statement has two implications: i) entropy is not conservative in general and ii) the non-conservative changes of entropy are only increases. In reversible situations, entropy is conservative. By contrast, irreversibility leads to the concept of entropy production: a net increase of entropy that does not stem from flows with the surroundings.

Here again, being conservative is not the same than being conserved, and entropy production is the departure from entropy being conservative. Nicolis and Prigogine (1977) showed that a system can produce entropy continuously and still be stationary if the entropy produced flows to the surroundings. Here, the entropy of the system is conserved, but it is not conservative. Similarly, the entropy of a system can decrease when work is used to this end. For example, centrifugation separates compounds of a gas or a liquid.

The second principle of thermodynamic captures the idea that heat can only go from warm bodies to cold bodies. The entropy change due to a heat exchange Q is $dS = Q/T$, where S is the entropy, and T is the temperature. Then, if we have

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[1]This efficiency is defined as the work produced divided by the heat taken from the warm source.

[2]The concept of a time arrow is somewhat abstract. Intuitively, there is a time arrow if we can tell whether a movie is played forward or backward by fundamental principles (Gayon and Montévil, 2017).

a isolated system with two bodies at temperature $T_h > T_c$, exchanging heat, then $dS = Q_{c \to h}/T_h + Q_{h \to c}/T_c$. We assume that the objects are only exchanging heat between each other so that $Q_{c \to h} = -Q_{h \to c}$. The only way for dS to be positive is if $Q_{h \to c}$ is positive; that is, the energy is going from the warm body to the cold body.

In classical thermodynamics, the central concept is thermodynamic equilibrium. At equilibrium, there are no macroscopic net fluxes within the system and with the system surroundings. For example, if we consider an open room, thermodynamic equilibrium is met when temperature, pressure, and other variables are homogeneous and the same as the surroundings. There are always exchanges of gas with the surroundings, but on average, there are no fluxes. By contrast, Nicolis and Prigogine (1977) describe stationary configuration far from thermodynamic equilibrium because there is a net flow of entropy from the system to the surroundings.

Thermodynamic equilibrium is typically the optimum of a function that is the combination of state variables appropriate for a given coupling with its surroundings. For example, entropy is maximal for an isolated system at thermodynamic equilibrium. Helmholtz free energy F describes the useful work that can be obtained from a system at constant temperature and volume. Let us discuss $F = U - TS$ where U is the internal energy. TS corresponds typically to the energy in the thermic form so that F is the energy minus the internal energy in thermic form. Spontaneously, Helmholtz free energy will tend to a minimum. This property is used in engineering to design processes leading to the desired outcome.

Helmholtz free energy is not the most commonly used function. Consider a battery in ordinary conditions; its purpose is to provide electrical work to a circuit, a smartphone say. Part of the work that can be performed by the battery is its dilation, which will push air around it. However, this is not genuinely useful. This kind of situation leads to the definition of Gibbs energy, the maximum amount of non-expansion work that can be obtained when temperature and pressure are set by the surroundings, $G = F + pV$, where p is pressure and V is volume.

In these examples, couplings with surroundings are a manifestation of technological purposes. Sometimes, the concept of exergy is used to describe available energy in general. Unlike Helmholtz and Gibbs free energy, exergy is not a function describing the state of a system because it depends on the coupling with the system surroundings. it depends on circumstances and can be aggregated in general.

Classical mechanics is deterministic and provides the complete trajectories of the objects described. By contrast, thermodynamics only determines the final state of a system by the minimization of the appropriate function. Since this state is singularized mathematically as an extremum, theoreticians can predict it. The epistemological efficacy of this theory lies precisely in the ability to determine final states. A system can go from the initial situation to the final situation by many paths, but the outcome is the same. Calculations are performed on well defined, theoretical paths, whereas actual path may involve situations such as explosions where variables like entropy are not well defined (they are defined again at equilibrium).

Classical thermodynamics is about final states at thermodynamic equilibrium. There is no general theory for far from thermodynamic equilibrium situations. The study of these situations may or may not use thermodynamic concepts. For example, biological evolution or linguistic phenomena all happen far from thermodynamic equilibrium, but their concepts are not thermodynamic. By contrast, non-equilibrium thermodynamics such as the work of Nicolis and Prigogine (1977) use concepts of thermodynamics. Unlike classical thermodynamics, these approaches need to introduce an accurate description of the dynamics. A standard method is to assume that small parts of the system are at

or close to thermodynamic equilibrium, but that globally the system is far from it.

To sum this discussion up, entropy is abstractly similar to a fluid to an extent. The limit of this analogy is that entropy is not conservative and spontaneously tends to a maximum in an isolated system. We do not genuinely consume energy; we are producing entropy. However, this does not lead to a straightforward accounting of entropy production on Earth. Earth is far from equilibrium, and its entropy is not well defined. Locally, exergy (usable energy) is not a state function since it depends on the couplings between a system and its surroundings. It follows that we cannot aggregate exergy between systems with a different nature. Nevertheless, in the comparison of physically similar, local processes, entropy production and exergy are relevant and necessary concepts.

In this context, it is interesting to note that an increase in temperature leads to an increase in entropy. As such, if Earth's entropy were defined, global warming would increase it. At the same time, Earth is exposed to the cold of space vacuum and loses heat this way. The greenhouse effect slows down this process, and thus slows down the corresponding production of entropy (released in open space). Accordingly, if we had a machine that was using the heat of the Earth surface as a warm source and the open space as a cold source, global warming would lead to more usable energy. Of course, this principled analysis has no practical counterpart. With this last example, we aim to emphasize again that the assessment of entropy and entropy production should be performed with respect to technological or biological processes.

2.1.2 Microscopic interpretations of entropy

The thermodynamic perspective described above is somewhat abstract; however, it has two microscopic interpretations which were introduced by Boltzmann and Gibbs, respectively. Debates on which of this interpretation is more fundamental are still ongoing, and their prevalence also has geographical differences (Goldstein et al., 2019; Buonsante et al., 2016). For large isolated systems, they lead to identical conclusions despite their conceptual differences. Both are bridges between microscopic and macroscopic descriptions. Here, we assume that the microscopic description is a classical, deterministic dynamics, and we do not address the quantum case.

Let us start with Boltzmann's interpretation of entropy. We consider gas in an insulated container so that its energy is constant. At the microscopic level, molecules move and bump on each other and the walls of the container chaotically. At this level, particles are described by their positions and velocities in three dimensions. These numerous quantities define together the microstate, X, and the micro space, i.e., the mathematical space of possible microstates. Let us insist that the microstate is not small; it describes all particles, thus the whole system. Then, we define the possible macrostates. For example, we posit that one macrostate corresponds to a uniform concentration of the molecules at a given scale and with a given precision. We can define another macrostate where all the particles are in the corner of the box, and one that encompasses all other possibilities. Depending on the microstate X, we will be in one of the three possible macrostates.

Let us follow Boltzmann and call $\Omega(X)$ the volume of the micro space that corresponds to the same macrostate than X. There are two crucial points in Boltzmann's reasoning on Ω.

First, the microscopic volume of a particular macrostate is overwhelmingly higher than the one of others. This situation is a mathematical property that stems from the huge number of particles involved. As a mathematical illustration, let us throw coins. Heads are 1, and tails are 0. The macroscopic variable is the average of the result after

a series of throws, which can go from 0 to 1. The first macrostate (M_1) is met when this average is between 0.48 and 0.52. All other possibilities lead to the other macrostate (M_2). With four throws we get, for example $0011 \to 0.5$ (M_1), $0110 \to 0.5$ (M_1), $0010 \to 0.25$ (M_2), $1110 \to 0.75$ (M_2), $1110 \to 0.75$ (M_2) and so on. The macroscopic results are quite random. However, for 10000 throws, with simulations, we get 0.493 (M_1), 0.499 (M_1), 0.505 (M_1), 0.512 (M_1), 0.498 (M_1) and so on. The system is always in the first macrostate even though it covers a small part of the possible macroscopic values.

Second, Boltzmann assumes molecular chaos: the system explores the micro space uniformly. It follows that the time spent by the system in a given macrostate is proportional to the microscopic volume of this macrostate.

Since one macroscopic possibility corresponds to an overwhelming part of the micro space, the system will spontaneously go in this domain and remain there except for possible, rare and short-lived periods called fluctuations. The largest the number of particles, the rarest fluctuations are. In typical situations, the number of particles is not 4 or 10000, but is closer to 100000000000000000000; therefore, fluctuations do not matter.

$\Omega(X)$ tends to a maximum with vanishingly rare fluctuations. It is a way to interpret the second principle of thermodynamics, which states that entropy cannot decrease in an isolated system. For example, why all air molecules are not in one corner of the room? Because all microscopic situations are equally likely and there are far more microscopic configurations that correspond to a uniform concentration of air than any other macrostate, see figure 1.

As pointed out by Chibbaro et al. (2014), this notion is very intuitive. For example, when playing pool, the initial situation is improbable, and we spontaneously think that somebody had to order the pool balls for them to be in a triangle shape. After striking them, their configuration becomes more uniform, and we acknowledge that it is the result of multiple random collision. The same qualitative result will follow if we throw balls randomly on the table. It is the same for velocities. Initially, only the ball struck is moving, and all others are still. After the collision, the kinetic energy is distributed among the balls until friction stops them. Of course, the goal of the game is to go beyond randomness and players aim for balls to reach specific locations.

The number of possibilities Ω is a multiplicative quantity. For example, if we throw a coin, there are 2 possibilities, but if we throw three coins, there are $2 \times 2 \times 2 = 8$ possibilities. This mathematical situation does not fit with the idea that entropy is proportional to the size of a system, which is part of the classical definition. The logarithm function transforms multiplication into addition, so $\log(\Omega_1 \times \Omega_2) = \log(\Omega_1) + \log(\Omega_2)$. Then $\log(\Omega)$ fits the properties of entropy, and we can state with Boltzmann that:

$$S = k_B \log(\Omega(X)), \text{ where } k_B \text{ is a constant}$$

Of course, there are many refinements of this approach to entropy. Here, for example, we considered that the total energy is conserved, whereas it is not always the case. Then, the definition of macrostates must include energy.

Gibbs proposed a different conceptual framework to interpret thermodynamic entropy (Goldstein et al., 2019; Sethna, 2006). Instead of studying a single system, Gibbs study an ensemble of systems, where we describe microstates by their probabilities.

In particular, the fundamental postulate of statistical mechanics states that all microstates with the same energy have equal probability in an isolated system. This
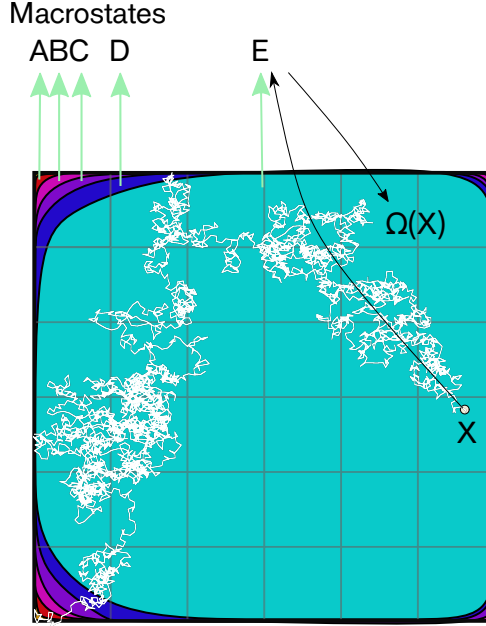
Figure 1: *Illustration of Boltzmann entropy.* Here, the micro space is represented schematically in 2 dimensions, and colors represent the corresponding macrostates. The system starts from a microstate associated with macrostate A. It explores microstates uniformly and soon arrives in positions corresponding to the macrostate E because most microstates correspond to E. For a microstate X, the number of configuration leading to the macrostate is $\Omega(X)$ (in light blue). Note than in physical cases, the micro space is not in 2 dimensions but has a huge number of dimensions — it is often the space of positions and momenta of all molecules, which leads to $3 + 3 = 6$ quantity per particle.

ensemble is called the microcanonical ensemble — this is Boltzmann's hypothesis in a different conceptual context.

Then, except for temperature and entropy, the macroscopic quantities are averages of the microscopic quantities computed with the probabilities defining the ensemble. The Gibbs entropy is defined by:

$$S = -k_B \sum_i \rho_i \log(\rho_i), \text{ where } \rho_i \text{ is the probability of the microstate } i$$

Despite their formal similarity, Gibbs and Boltzmann's formulations have a critical difference. In Boltzmann's formulation, a single microstate has an entropy: a microstate corresponds to a macrostate, this macrostate corresponds to many microstates, and how many define the entropy of the said microstate. By contrast, Gibbs framework is not about individual microstates, and we consider all possible microstates simultaneously. Some are more probable than others, and entropy is about the probabilities assigned to the microstates. For example, when the system is isolated, and its total energy is constant, all microstates with the same energy have equal probability, and this maximizes the entropy.

In a nutshell, the entropy being maximal is a property of the state of the system for Boltzmann. By contrast, it is a property of an ensemble of systems for Gibbs, and more specifically, it is a property of the associated probabilities. In mathematically favorable conditions (infinite number of particles), the outcome is the same despite this significant
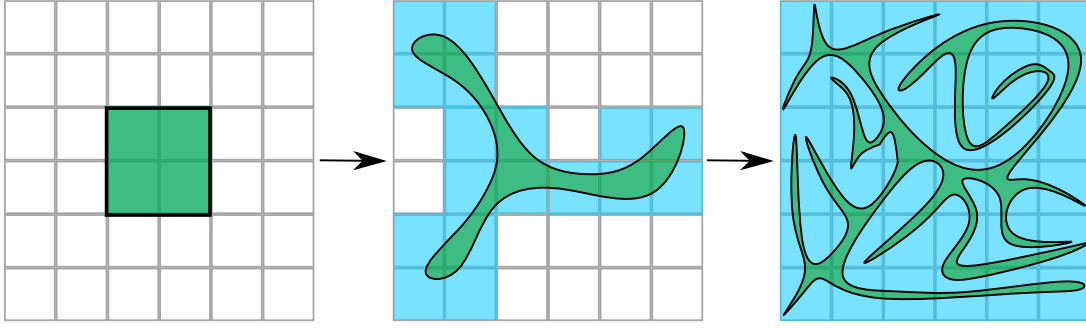
Figure 2: *Coarse-graining versus Liouville's theorem.* As in figure 1, space is represented schematically in 2 dimensions. The micro space is coarse-grained by a grid. The systems are initially in a small part of the micro space, which corresponds to four boxes of the coarse-grained grid. After some time, the initial volume has deformed without expanding at the fine-grained level in green. However, the coarse-grained volume occupied by the systems has expanded in blue. After more time, the fine-grained volume has become highly convoluted and meets the whole coarse-grained space, in blue. The growth of the coarse-grained volume occupied by the systems is the argument explaining the growth of Gibbs entropy.

conceptual difference.

Gibbs formulation presents a hidden challenge. Liouville's theorem's states that the probabilities in an initial volume in the micro space are conserved over the dynamics. It follows that this volume cannot shrink or expand over time. Taken as is, this would mean that the entropy cannot increase over time — an embarrassing result when aiming to interpret the second principle of thermodynamics.

The leading solution to this problem is a procedure called coarse-graining. Let us introduce it by an analogy. Water occupies a small volume in the tank of a spray bottle. Once water is sprayed, a tissue in the air affected is going to be wet. From the perspective of the tissue, water occupies a vast volume of air. Nevertheless, the actual volume of liquid water remains the same; water has just been dispersed, not added. This example shows that there are two ways to understand the volume of water: the fine-grained volume of water that remains the same, and the volume of air where the moving tissue will meet water this volume increases. Mathematically, if we partition space in boxes, all these boxes will contain some of the sprayed water. This procedure is called a coarse-graining. The fine-grained volume of water remains the same, but the coarse-grained volume has expanded (figure 2).

Technically, the microstates are not represented individually in the calculation of entropy because entropy would not change over time as a result of Liouville's theorem. Instead, physicists use a coarse-grained representation of the system, where probabilities describe each volume. The dynamics still preserve the fine-grained volume; however, the latter deforms, gets more and more convoluted over time, and meets more and more coarse-grained volumes (the boxes). As a result, the coarse-grained volume increases, and so does the entropy (figure 2).

Let us make several supplementary remarks.

First, the second principle of thermodynamic is imperative: the entropy of an isolated system cannot decrease. In Boltzmann's formulation, entropy can also decrease albeit overwhelmingly rarely. In Gibbs formulation, the equilibrium probabilities remain as such, so entropy can only increase.

Second, the concept of entropy in physics pertains to physics. The hallmark of this theoretical nature is the use of the constant k_B. k_B is the bridge between temperature, heat and mathematical entropy since an exchange of heat leads to $Q/T = dS = k_b d \log \Omega$. k_B bridges units of the International System of Units. Sometimes, a similar mathematical apparatus can be used, for example, to study flocks of bird or school of fishes (Mora and Bialek, 2011); however, this use is an analogy and does not convey the same theoretical meaning (Montévil, 2019c). The absence of k_B is evidence of this fact. Along the same line, in physics, the space of possible microscopic configurations inherited from mechanics is position and momenta, and other aspects can be added, such as molecular vibrations or chemical states.

Third, why does an isolated system tends towards maximum entropy, in a nutshell? Let us imagine that the system starts in a low entropy configuration. In Boltzmann's formulation, it will travel among microstates, and most microstates correspond to a single macrostate, which is the maximum entropy configuration (the microstate of a system explores the micro space uniformly). In Gibbs formulation, let us picture that initially, the ensemble of systems is confined to a single coarse-grained microstate. Over time, it will spread towards more and more coarse-grained microstates so that their probabilities will tend towards the equilibrium distribution, the one with maximum entropy.

In both cases, the macroscopic description of the object goes from a particular state towards the most generic configuration, and the increase of entropy erases the macroscopic peculiarity of the initial configuration. It erases the past. The increase of entropy corresponds to the spread among microstates towards more generic microstates. As such, we can interpret it as the dispersion of energy. Nevertheless, the increase of entropy is sometimes compatible with the appearance of macroscopic patterns. They can emerge due to energetic constraints, in the formation of crystals such as ice for example. However, to enforce further patterns, work is required. For example, the Earth's gravity field pulls heavier molecules to the bottom of a room, which has many implications for toxic gases.

Last, the articulation of the objective and subjective dimensions of entropy is a complex subject. Let us mention an interesting example given by Francis Bailly: when scientists discovered isotopes, seemingly equivalent particles could be distinguished. The macroscopic description changed, and so did the entropy. The decisive point is that previous predictions still hold. For example, if gas is initially in the corner of a room, it will spread in the room. However, we can make new predictions once we know that there are different isotopes. For example, if we see that only a given isotope is in the corner of the room, then we can predict that the corresponding entropy will increase and that the molecules with this isotope will spread in the room.

Along the same line, Boltzmann's formulation depends on the definition of macrostates. The latter depends on the coupling between the system and its surroundings. Similarly, Gibbs entropy depends on a coarse-graining, which also corresponds to the coupling between a system and its surroundings. Thus, entropy ultimately depends on these couplings. As a result, Rovelli (2017) argues that entropy and the corresponding time arrow are perspectival, where the perspectives are not merely subjective but stem from the couplings with surroundings. In the case of technlogies, the choice of the couplings depend on the purpose of the device, as discussed above.

2.2 Dispersion and concentration of matter

In this section, we will discuss how entropy underlies the theoretical understanding of mineral resources. This case is relatively simple since we are mostly concerned with the phenomena of dispersion and concentration of matter.

Georgescu-Roegen (1993) struggled with this question and even considered a possible fourth law of thermodynamics to state that perfect recycling is not possible. The current consensus is that this point is not valid (Ayres, 1999; Young, 1991).

For example, Ayres (1999) argues that a "spaceship" economy is possible in principle. In this mind experiment, free energy comes from outside *ad libitum*, and the matter is recycled thanks to this energy indefinitely. We mostly agree with this perspective except on a specific point. If the system has to materialize its own boundaries (the shell of the spaceship, or the atmosphere of the Earth), then these boundaries will be exposed to the void of space and will be eroded — a phenomenon producing entropy. For example, the Earth loses parts of its atmosphere continuously. However, this is more a principled issue than a practical one, and it does not depend significantly on human activities.

At a more fundamental level, there is no sharp distinction between energy and matter, as explained by Einstein's equation $E = mc^2$. For example, the very slow decay of protons is the destruction of what we usually consider as stable matter: it is a process of entropy production.

2.2.1 Ore deposits

Despite these controversies, entropy is a critical concept to understand mineral resources. In this section, we build mainly on the analysis of ore deposits formation in geochemistry (Heinrich and Candela, 2014).

Non-radioactive atoms are conserved in chemical changes; therefore, human or biological activities do not alter their abundance on Earth.[3] The problem of resources, here, is similar to the one of energy: what matters is not the quantity of the intended atoms existing on Earth. It is mostly their configurations.

When analyzing ore deposits, the critical factor is the concentration of the intended ores. The higher the concentration of an ore deposit is, the less chemical and mechanical work is required to purify it to useful levels, and, accordingly, the higher its profitability is. If the local concentration of ores in the Earth crust was equal to its average everywhere, then even the most common resources could not be extracted fruitfully. Then, it is the departure from situations of maximum entropy, as far as the concentrations of ore are concerned, that is the crucial factor in analyzing mineral resources.

What is the origin of the heterogeneities that leads to usable ore deposits? If we consider lava of the average composition of the Earth, in an insulated box, such deposits would not appear spontaneously because of the second principle of thermodynamics. However, the Earth is not in thermodynamic equilibrium. The nuclear fission of some of its components warms its insides up — a transitory but prolonged process. Moreover, it is an open system. The Sun provides energy on its surface. The space vacuum acts as a cold source where energy is lost, mostly in the radiative form. Between cold sources and warm sources, macroscopic motions occur spontaneously leading to convection cells. They happen in the mantle, the oceans, and the atmosphere. Convection is just an example of a macroscopic phenomenon that occurs spontaneously in open systems far from thermodynamic equilibrium, and specifically on Earth. Another example is the

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[3]We put radioactive elements aside because radioactivity leads to the fission of atoms, thus their destruction.

cycle of water, which involves state changes.

These various macroscopic phenomena can lead to the magnification of ore concentration, often as a result of a contingent combination of processes. For example, heavy compounds tend to sink to the core of the Earth; however, melted magma rises as a result of convection in the mantle. In magma chambers, gravitation leads heavier elements to sink and thus to the appearance of heterogeneities. Later, the resulting rocks can be submerged or exposed to rainwater, and some compounds will dissolve. If the elements of interest dissolve, they may precipitate at a specific location where appropriate physicochemical conditions are met, leading to an increased concentration. Alternatively, some elements, for example, gold, may not dissolve in most situations, but other compounds surrounding it may dissolve and be washed away, exposing gold and increasing its local concentration. Then, gold nuggets can be transported by water and concentrated further in specific places in streams — a key and iconic factor of the American gold rush. In general, ore deposits are the result of such combinations of processes (Heinrich and Candela, 2014; D.Scott et al., 2014).

In a nutshell, ore deposits are the result of macroscopic phenomena that occur on Earth because it is far from thermodynamic equilibrium. Human activities take advantage of this naturally occurring process and pursue it further by several industrial methods that produce very high concentrations in the intended element. All these processes require macroscopic work and generate entropy.

2.2.2   Wear and entropy

In the use of artifacts, wear can lead to the dispersion of the compounds of the objects used. For example, the emission of fine particles from motor vehicles stems as much from the wear of tires and breaks than from the combustion engines (Rogge et al., 1993).

The wear of mechanical components stems from the transformation of part of the mechanical work into heat, leading to a production of entropy. Part of this entropy is released on the surroundings as heat. Another part increases the entropy of the component. Entropy production at the level of the elements of a machine is a general framework to understand the wear caused by their use (Bryant et al., 2008; Amiri and Khonsari, 2010). Similar phenomena occur in electronics and microelectronic. Electric currents increase the probability that atoms move in the components, leading to higher entropy than in the designed configuration, and ultimately to component failure (Basaran et al., 2003). A similar phenomenon also occurs in batteries and explains their "aging" (Maher and Yazami, 2014).

Another compelling case is the appearance of microplastics at increasingly high levels in seawater. The origin of these microplastics seems to be in the water of washing machine when washing synthetic textiles (Browne et al., 2011). The resulting concentration in the environment is sufficient to threaten wildlife (do Sul and Costa, 2014).

All these examples show that artifacts are altered over time because their use strains them. Moreover, this alteration can result in particles that are dispersed in the surroundings and threaten human and wildlife health. All these phenomena are entropy increases.

2.2.3   Bioaccumulation, bioconcentration, biomagnification

Living beings, especially bacteria, can contribute to the formation of ore deposits by their biochemical activities. However, there is another relevant extension of this discussion in the biological realm. Biotic processes can concentrate compounds released in the environment by industrial processes and products. The accumulation of such

compounds in biological organisms impacts their survival and the safety of their consumption by humans.

Several processes are involved in this phenomenon (Barron, 2003). The first is the bioaccumulation from sediments. This process is very relevant for heavy compounds that sink to the ocean floor, such as heavy metals or microplastics. It largely depends on the behaviors of the organisms involved. Some of them, like worms, can ingest relatively old sediments whereas other organisms feed at the surface of sediments.

The second process is the bioconcentration from compounds present in water. Some compounds existing in water have a higher affinity with particular organs or tissues than with water itself. As a result, even assuming that equilibrium between intake and excretion of the said compound is reached, they are in higher concentration in organisms than in water. For example, lipophilic and hydrophobic compounds such as PCBs accumulate in fat tissues.

The bioaccumulation from sediments is made possible by the feeding activity of organisms, a process far from thermodynamic equilibrium. Similarly, bioconcentration from water stems mostly from the fast chemical exchanges taking place during respiration, at the level of gills for large organisms. In both cases, accumulation is made possible by the specific chemical compositions of organisms. The latter are generated and sustained by organisms — a process far from thermodynamic equilibrium. Depending on the cases, the concentration inside the organism can reach a balance between the intake and release. On the opposite, organisms can collect compounds in their milieu without reaching the equilibrium concentration.

The last relevant process is biomagnification in food chains. Living beings feed on each other. Bioaccumulation from sediments and bioconcentration lead to the presence of compounds in prey organisms. Then, these compounds become part of the food of a predatory organism and can accumulate further in the latter. This process follows the food chain magnifying the concentration of the compound that gets higher than in sediments and water. The bioaccumulation of heavy metals and PCBs leads to organisms that are improper for consumption.

In these examples, the concentration of metals and chemicals is increased dramatically by biological processes. There is a reduction of the entropy of their spatial distribution. This process is detrimental to the biosphere in general and humankind in particular.

2.2.4 Conclusion

There are geological processes that occur far from thermodynamic equilibrium. These processes lead to a distribution of compounds that is far from what we would expect by a straightforward application of the second principle of thermodynamics. Humankind takes advantage of this situation and extract ores from deposits with sufficient concentrations, and concentrate them more by industrial processes. However, processes such as the wear of artifacts also lead to the dispersion of various compounds in the biosphere.

The presence of these compounds at these concentrations is new from an evolutionary perspective, and there is no specific biological process stemming from evolution that mitigates their consequences. Depending on their properties and the physiology of the organisms exposed, they can lead to bioaccumulation, bioconcentration, and biomagnification in the food chain. These processes lead to a high concentration of several compounds at the worse possible locations for biodiversity and humankind: in the body of organisms. In these cases, the decrease of the entropy corresponding to the concentration of these compounds is detrimental.

2.3 Conclusion

In a nutshell, entropy describes the degradation of energy in physics. This degradation means going from unlikely macrostates towards more likely macrostates, that is to say, from specific configurations to more generic ones.

Defining entropy requires the articulation between microstates and macrostates. Theoretical choices of macrostates are based on their causal role, and the latter depends on the couplings with surroundings. Therefore entropy also depends on the nature of these couplings. Moreover, available energy, exergy, depends not only on the nature of the variables involved in these couplings but also on their values. Nevertheless, some couplings and macroscopic descriptions are generic to a large extent for technological purposes; for example, the mobility of persons and goods leads to analyze macroscopic mechanical couplings.

In engineering, entropy typically comes into play to analyze the functioning of a machine, starting historically with heat engines. However, the production of machines also involves entropy, as exemplified by our discussion on mineral resources. This remark connects with the biological concept of autopoiesis: an organism has to maintain or regenerate its parts. The design of machines is also external to the analysis of functioning machines, and the function of machines and artifacts can change depending on the user, beyond generic analyses of their use. These ideas are reminiscent of biological evolution. Taking all these aspects into account leads to a more biological view of technologies. Ultimately, available energies (exergy) depends on a given technological apparatus, and the problematic increases of entropy are relevant from the perspective of technological, social, and biological organizations.

3 Entropy and organizations

Schrödinger (1944) emphasized that biological situations remain far from thermodynamic equilibrium. There is no contradiction with the second principle of thermodynamics because biological systems are open systems that can release entropy on their surroundings. We already discussed macroscopic movements of matter on Earth that occur spontaneously far from thermodynamic equilibrium and sometimes lead to the formation of ore deposits, thus to low entropy configurations.

Schrödinger went further and proposed to analyze biological order as a negative entropy. There are little doubts that biological organizations correspond to a low entropy insofar as we can define their entropy. There have been several theoretical works along this line (Nicolis and Prigogine, 1977; van Bertalanffy, 2001). However, conflating low entropy and the concept of organization is not accurate. Everything that contributes to the low entropy of biological situations is not relevant for their organizations. For example, the growth of a cancerous tumor is an increase of morphological complexity, but a decrease in organization (Longo et al., 2015). Similarly, we have discussed biomagnification and other processes that reduce the entropy of chemicals spatial distribution but are detrimental to biological organizations. Moreover, entropy is extensive; it is proportional to the size of a system. By contrast, critical parts of a biological organization may not amount to much quantitatively, such as a single nucleotide or a few molecules in a cell.

This kind of shortcomings led to propose another quantity to address biological organizations: anti-entropy (Bailly and Longo, 2009; Longo and Montévil, 2014a). Anti-entropy was first a macroscopic extension of far from equilibrium thermodynamics. The term anti-entropy stems from an analogy between the relation matter/anti-matter and

entropy/anti-entropy. Entropy and anti-entropy are similar, they have an opposite sign, and at the same time, they have a qualitatively different meaning. They only "merge" when the organism dies or, more generally, when an organization collapses.

To go further, we have to introduce several theoretical concepts designed to understand biological organizations and discuss their articulation with entropy. Then, we will show that the nature of biological organizations leads to two specific kinds of vulnerabilities to the changes of the Anthropocene.

3.1 Theoretical background

We first discuss couplings between biological organizations and their surroundings, provided that it is a crucial element in the definition of entropy. Then, we discuss the nature of putative biological micro spaces and show that they lead to introduce the fundamental concept of historicity. Last, we address how organizations maintain themselves far from thermodynamic equilibrium by the interdependencies between their parts.

3.1.1 Couplings with the surroundings

The couplings between a system and its surroundings are critical to defining entropy and thermodynamic equilibrium, as discussed in section 2.1.2. However, in biology, the couplings between organisms and their milieu is a far more complex theoretical notion.

First, biology requires to historicize the concept of coupling. Couplings change in evolution and development. It is even tempting to consider specific principles (Kirchhoff et al., 2018). Once living objects are exposed to phenomena that impact their organization, they will tend to establish couplings with these phenomena in a diversity of ways. For example, some phenomena can be a source of free energy. It is the case of light, which enabled photosynthetic processes. Similarly, humans have recently concentrated radioactive compounds for industrial purposes. In Chernobyl, Ukraine, wildlife was exposed to these compounds, and fungi appeared that metabolize their intense radiations (Dadachova et al., 2007). However, couplings are not limited to significant sources of free energy. For example, light is also used by many organisms to perceive their environments.

In these examples, the inside and the outside of an object are well-defined. However, the organisms' surroundings are not just static. Instead, organisms change them actively. With the ability to move, organisms can discover and secure different surroundings. In the process of niche construction, they actively produce part of their surroundings (Odling-Smee et al., 2003; Pocheville, 2010; Bertolotti and Magnani, 2017). Beyond the concept of coupling between inside and outside, biology involves couplings between different levels of organization. These couplings stem from a shared history, for example, between a multicellular organism and its cells, and organisms and ecosystems (Soto et al., 2008; Longo and Montévil, 2014b; Miquel and Hwang, 2016).

In a nutshell, physicists established thermodynamics for systems where the coupling between a system and its surroundings is well defined and is usually static. This framework enables engineers to control industrial processes and artifacts. By contrast, the coupling between living organizations and their surroundings is not well defined. It is not an invariant of the object. Current couplings are the result of natural history, and continue to change, producing history (Miquel and Hwang, 2016; Montévil et al., 2016). In ecosystems, the appearance of a species present many opportunities for new couplings, that is to say, new possible niches (Longo et al., 2012; Gatti et al., 2018). We can include social organizations and their production of artifacts in the discussion — artifacts are analyzed as exosomatic organs by Lotka (1945). Then, living matter has

coupled some of its processes, the activity of physicists, to remarkably weak phenomena at biological scales such as gravitational waves or interactions with neutrinos.

Couplings are far more proteiform in biology than in the standard framework of thermodynamic. In the case of artifacts and industrial processes, let us recall that the thermodynamic couplings correspond to the purpose of the said processes in order to generate useful work. In this context, the plasticity of biological couplings corresponds to the variability of biological functions that is intrinsic to the historical changes of biological objects.

3.1.2 Micro spaces in biology

The situation for candidate micro spaces in biology differs from the basic hypotheses used to define entropy.

First, space is materially broken down by membranes at all scales, from organelles and cells to tissues, organs, and organisms. This spatial organization restricts diffusion and the rate of entropy increase. In turn, this partial compartmentation ensures that for many kinds of molecules, the number of molecules remains small in compartments such as cells. Chromosomes, in particular, exist in only a few copies in each cell. We have seen with the example of coin throwing that a macroscopic variable was stable in the case of a high number of throws but highly random for a small number of throws. It is the same for molecular processes in cells, and the low number of molecules leads to randomness (Kupiec, 1983; Kaern et al., 2005; Corre et al., 2014). This randomness, in turn, implies that the deterministic picture for collections of molecules in cells is not sound (Lestas et al., 2010).

Second, the complexity of cellular proteomes includes networks of numerous compounds interacting and exhibiting complex dynamics (Kauffman, 1993; Balleza et al., 2008). To an extent, these dynamics can even "improvise" when, for example, the regulation of a gene's expression is artificially jammed (David et al., 2013; Braun, 2015).

Last, the nature of the molecules existing in cells and organisms is not a theoretical invariant. As a result, we have to take into account the changes in the relevant molecules. For example, proteins are chains of amino acids. If we consider only proteins with 200 amino acids, there are 22^{200} possible molecules. This number is gigantic: if all the particles of the universe (10^{80}) were devoted to exploring this space of possibility by changing at the Planck time scale, they would not manage to explore much of this space in the universe lifetime (Longo et al., 2012). Unlike Boltzmann, we cannot build on the idea that microscopic possibilities would be explored uniformly, leading towards generic configurations (the most probable macrostate). Instead, we have to focus on how systems explore possibilities in a historical process.

If the difficulty were limited to this aspect, it would not genuinely hinder the use of mathematical reasoning to find generic patterns. For example, mutations without selection (neutral mutations) lead to a random walk in the space of possible DNA sequences, and probability distributions describe this process well. Its generic properties are used to assess the genealogical proximity of different species. Similarly, we can analyze the generic properties of large networks of interacting molecules if the interactions are generic; i.e., all have the same nature.

The problem is that this process leads to molecules with qualitatively different behaviors. For example, molecular motors or tubulin do very different things than enzymes. Molecular motors are molecules that "crawl" on macromolecular structures and tubulin are molecules that constitute fibers spontaneously. Moreover, molecules contribute to macroscopic structures and interact with them. In this process, their biological mean-

ings acquire qualitative differences. For example, crystallin proteins contribute to the mechanical integrity of the eye, and they are transparent so that they do not hinder the flow of light.

In the relevant organic and ecosystemic contexts, the specific properties of proteins impact the process of exploration of DNA sequences. As a result, the latter differs from a random walk, and its determinants are multiple. Even the dynamic of neutral mutations changes because the way mutations occur, can be inverted or prevented, and the process of reproduction do change.

We consider how living beings live as the central interest of biology. Therefore, functionally relevant changes are fundamental. In the case of mutations, biologically relevant variations are the one that impacts biological organizations in one way or another. When we discuss the primary structure of proteins (their sequence) or DNA sequences, we consider combinations of elementary elements, like a text is a combination of letters and other symbols. If we take this process of construction alone, all combinations seem equivalent, which wrongly suggests an analogy with Boltzmann's hypothesis of molecular chaos. In biology, these combinations are not biologically equivalent. They can lead to qualitative novelties and changes in the exploration of these combinatorial possibilities. In a nutshell, not only is the space of combinatorial possibilities massive, but the "rules" of the exploration of this space depend on positions in this space — and these positions are not the sole determinants. These rules are as diverse as functional biological processes are, and thus are not generic (Montévil et al., 2016; Montévil, 2019b).

The epistemological and theoretical consequences of this situation are far-reaching, and there is no consensus on the appropriate methods and concepts to accommodate them (Bich and Bocchi, 2012; Montévil et al., 2016; Longo, 2018; Kauffman, 2019).

We have proposed to invert the epistemic strategy of physics. Physics understand changes by invariance: the equation and their invariants describe changes of states but do not change themselves. By contrast, in biology, we argue that variations come first, and that (historicized) invariants come second. We call the latter "constraints" (Soto et al., 2016; Montévil, 2019c). We have argued that, unlike in the theories of physics, the definition of concrete experiments always has an essentially historical component in biology. In physics, experiments can be performed *de novo*, whereas biological experiments and their reproducibility rely on objects having a common origin, thus on the ability of organisms and cells to reproduce (Montévil, 2019a).

In particular, the space of possibilities cannot be pre-stated both at the microscopic and macroscopic levels — provided that stating possibilities requires to state their causal structure explicitly. For example, the space generated by molecular combinatorics is not genuinely a space of possibilities. It is not endowed with a proper causal structure able to state explicitly that molecules like molecular motors or tubulin are possible. Moreover, this space is far from complete, for example, proteins longer than 200 amino acids exist, and proteins can recruit other elements such as iron in hemoglobin or iodine in thyroid hormones. Nevertheless, this space is relevant: it is a space of possible combinations of amino acids. This space is generated mathematically by the enzymes defining the processes of transcription and translation (Montévil, 2019b). However, this theoretical construct is insufficient to state the possible roles of the said combinations in biological organisms. In this regard, possibility spaces in biology are not just a way to accommodate changes; they are part of biological changes and are co-constructed by them.

3.1.3 Persisting organizations

Several theoretical biologists have developed the idea that the parts of a biological organization maintain each other (Varela et al., 1974; Rosen, 1991; Kauffman, 1993; Letelier et al., 2003). In particular, Kauffman (2002) articulates constraints and work in the thermodynamic sense. In Kauffman's schema, work maintains constraints and constraints canalyze work. This interdependency leads to the persistence of work and constraints as long as the surroundings allow it.

We have developed a general and formalized framework describing the interplay between processes of transformations and constraints. In this framework, a constraint is invariant w.r. to a process, at a given time scale, but it canalyzes this process. A constraint C_1 can act on a process that maintains another constraint C_2. Then, we say that C_2 depends on C_1. We hypothesized that relations of dependence in organizations lead to cycles. For example, C_1 depends on C_2, C_2 depends on C_3, and C_3 depends on C_1 (Montévil and Mossio, 2015; Mossio et al., 2016). We call this kind of circularity closure of constraints.

Closure of constraints is very different from being closed in the thermodynamic sense. Organizations depend on flows from the surroundings at the level of processes to remain far from thermodynamic equilibrium. For example, mammals depend on food and oxygen flows. They also depend on external constraints that are necessary to sustain internal constraints but are not maintained by the closure. For example, many organizations depend on the physical periodicity of night/day cycles.

Constraints are not necessarily macroscopic (and thus thermodynamic). Constraints are patterns structuring processes of transformation; they can exist at all space and time scales. For example, DNA sequences are constraints on gene expression. DNA 3D configurations influence the accessibility of genes and are also constraints on gene expression. Similarly, the geometry of the vascular system is a constraint on blood flow in tetrapods.

In this framework, biological entities maintain their configuration far from thermodynamic equilibrium in a distinct way. Let us recall that, in physics, a configuration far from thermodynamic equilibrium can appear and persist by the self-organization of flows stemming from their surroundings. It is the case in convection cells, for example. Biological organizations last for different reasons. In the framework of the closure of constraints, organizations persist thanks to the circular interdependencies between constraints. They are not the result of spontaneous self-organization of flows (Longo et al., 2015).

Organizations are not spontaneous also in the sense that they stem from history. Self-organization in physics is generic; for example, convection cells always follow the same pattern at the right level of analysis. By contrast, closure of constraints is compatible with many qualitatively different configurations. For example, different bacteria can live in the same milieu. Reciprocally, in the historicized epistemological framework that we have hinted to, invariants (constraints) cannot be postulated like in physics, they require an explanation. Closure of constraints is a way to explain the relative persistence of some constraints (Montévil et al., 2016; Mossio et al., 2016; Montévil, 2019c). Natural selection is another, complementary way to explain the relative stability of constraints.

Closure of constraints describes constraints collectively stabilizing each other. It does not follow, however, that the constraints of an organization remain static. On the opposite, there are limits to the stability of biological organizations. For example, intrinsic variations follow from the small number of most molecules in cells (Lestas et al., 2010). As a further illustration, let us consider a gene coding for a fluorescent

protein, but with a mutation preventing the formation of the said protein if the code is considered exact. However, it is not exact. Randomness in gene expression generates a diversity of variants, including the fluorescent protein, and bacteria presenting the mutated gene will be fluorescent (Meyerovich et al., 2010).

Actual biological organizations result from the iterative integration of novelties. Novelties are random in the sense that they cannot be predicted from the current state of affairs; however, they are not generic; as discussed above, they provide a specific contribution to organizations. Specificity stems both from the structure of constraints and their articulation to an organization.

3.1.4 Conclusion

In order to specify anti-entropy further, we propose to consider that an element relevant for anti-entropy satisfies three criteria. i) It contributes to organization *sensu* closure of constraints; informally, it has a systemic role in the persistence of the organism. ii) It is the specific result of history. iii) The specific properties in (ii) are the condition for the systemic role in (i).

It follows from this definition that anti-entropy is relative to an organization. A change that increases the anti-entropy of an organization can reduce the anti-entropy of another and even lead to its complete collapse.

There are two ways in which anti-entropy can be nonconservative. First, it can decrease, which leads to the production of entropy, the ultimate example being death. Second, by analogy with entropy production, we propose the concept of production of anti-entropy. Anti-entropy production corresponds to the appearance of novelties, as described above. This process is time-oriented, like entropy production.

There are processes in biology that are analyzed as physical self-organization, such as convection cells or Turing's morphogenesis (Turing, 1952). According to our definition, they do not contribute *per se* to anti-entropy: they are generic. However, their conditions of possibility and their role in other processes, such as cellular differentiation, can be relevant for anti-entropy. In the latter case, they are enabling constraints for the growth of anti-entropy. Here, we are following a line of reasoning similar to van Bertalanffy (2001). He distinguishes mechanized processes that lead consistently to a given result at the level of the parts and non-mechanized processes that involve the organism as such.

Last, anti-entropy production requires to produce a specific situation conveying a specific biological meaning. Such situations are not generic outcomes; therefore, they require work of exploration that can be either at the level of the new parts or by broader changes of organization. This exploration can be either at the level of an individual, a group, a population, or an ecosystem. In the particular case of humans, this exploration can be performed by intellectual work to an extent, using tools such as pens and papers or computers.

3.2 Disruptions as entropizations of anti-entropy

We will now discuss how this framework can contribute to understanding the Anthropocene crisis. Let us start with an example.

Seasonal variations constrain living beings and their activities. Biological responses specific to this rhythm appeared in evolution. The internalization of seasonal rhythms is an example of the trend to establish complex couplings that living beings exhibit, as discussed above. Many biological events such as blooms, hatching, and migrations
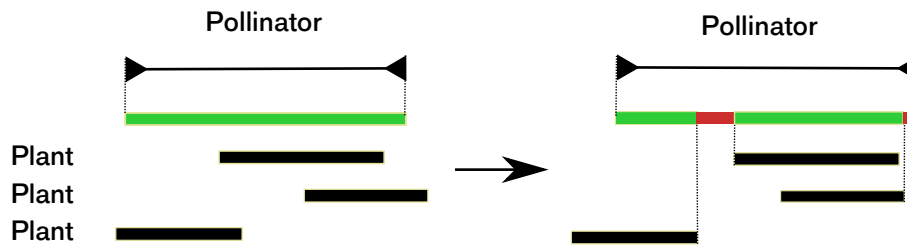
Figure 3: *Phenological differences between plants and pollinators after a change of climate (adapted from Jane et al., 2007).* Left, situation before the change. The pollinator is viable because there are plants that flower during all its activity period. Right, situation after climate change. The activity periods changed somewhat randomly. The pollinator has two parts of its activity period without a plant to pollinate which leads to its disappearance in the model.

take place at specific times of the year. The study of periodic events in the living world associated with seasonality is phenology.

In ecology, the "desynchronizations" of activities in an ecosystem can break down relations between populations in an ecosystem. These alterations and their consequences are often called disruption, and their study is a particularly active field of research. They are relevant economically, socially, and for conservation biology (Morellato et al., 2016; Stevenson et al., 2015).

We argue that understanding these disruptions supposes simultaneously to analyze i) the relations in a system and ii) the natural history which originates a specific synchronization iii) that contributes to the populations' viability. In other words, we think that disruptions decrease anti-entropy.

Let us describe the typical situation in more detail. If all populations would follow the same shift, then there would be no change in their interactions. However, species use a diversity of clues to articulate their behavior with seasons (called Zeitgeber, e.g., temperature, snow, soil temperature, and photoperiod Visser et al., 2010). The impact of climate changes on phenologies is diverse, because, for example, climate change does not impact photoperiods but does impact temperatures. The diversity in phenological changes impacts the possible interactions and can destabilize ecosystems.

For example, Jane et al. (2007) modeled the disruption of plant-pollinator interactions in an ecosystem. In this model, the notion of disruption has a precise meaning, which is not discussed by the authors. Let us describe their model. Each plant has a flowering period, and each pollinator has a period of activity. Plant-pollinator interactions stem from empirical data. A plant has to be pollinated by at least one pollinator to reproduce. A pollinator must have plants to pollinate during its whole period of activity to survive.

The outcome of this computational model is that few plants are vulnerable to the change, but many pollinators are. Plants are relatively robust because, during their flowering period, a single pollination event is sufficient for their survival. However, pollinators are vulnerable because they need to feed during their whole period of activity, see figure 3.

What happens in this model at a deeper theoretical level? The initial situation is in a small part of the space of possible activity periods because all plants and pollinators are in a viable configuration. The underlying history of these ecosystems explains that these particular configurations exist. The condition of viability for plants and pollinators

leads to a systemic analysis of their networks of interactions, at a given time. After a change in the local climate and the subsequent, diverse phenological offsets, a significant number of pollinators and some plants are no longer in a viable configuration. Here, the specific initial situation transforms into a more random or "arbitrary" configuration concerning the viability and Natural History. In this model, disruption is the dissipation of the result of history impacting the sustainability of systems parts.

The initial situation contributes to anti-entropy. The elements of the system contribute to their viability by plant-pollinator interactions (i). The initial configuration is specific because it is in a small part of the possibility space as a result of natural history (ii). Last, this specific configuration has an organizational meaning: in our example, all populations are viable because of them (iii). The initial configuration meets our three criteria; therefore, the specificity of the initial configuration is part of the anti-entropy of the ecosystem.

The final configuration is more generic than the initial one; it is more random concerning viability criteria. Climate change leads to the loss of part of the anti-entropy by the process of entropy increase in the space of activity periods.

There are many situations were similar reasonings take place to analyze disruptions of synchronicities, even though our theoretical interpretation is not explicitly used (for example, Robbirt et al., 2014; Rafferty et al., 2015; Jane et al., 2007).

Our discussion in terms of anti-entropy and its decrease in disruption is more general than the case of seasonal synchronicities. Climate change and other changes of the Anthropocene disperse part of the anti-entropy of biological organizations and produce entropy at the level of the relevant description space. The configuration after the change occupies a larger part of the description space than initially, and these configurations do not fit with the organization of the system (in our example, not all populations are viable).

Biological organizations have a particular vulnerability. They build on regularities, in particular, the ones in their surroundings. However, these regularities can change, and in the Anthropocene, they change very quickly as a result of human activities. In many cases, unlike in cybernetics, no feedback stabilizes these couplings, at least not on short time scales. When the surroundings change, fine-tuned organization become randomized and thus disorganized to an extent. A similar phenomenon occurs, for example, in the case of endocrine disruptors. Chemical industries produce new chemicals, some of which interfere with hormone action. Since these chemicals and family of chemicals are new occurrences in the biosphere, there is no organized response to them, and they tend to randomize hormone action. Endocrine disruptors lead to many adverse effects, both for human and wildlife (Zoeller et al., 2012).

We thus have a first organizational concept for the Anthropocene crisis: a partial loss of anti-entropy that corresponds to an increase of entropy. Here, entropy is not directly the concept of physics (i.e., with k_b): the growth of entropy occurs for biological quantities relevant for biological organizations. The loss of anti-entropy is the loss of specific results of history contributing to the current organization of organisms or ecosystems, leading to their disorganization.

3.3 The disruption of anti-entropy production

To introduce the last idea, let us start with examples from human activities.

Translations provide a simple, compelling example. Let us compare part of a recipe of Bourguignon beef with the text after multiple translations by Google Translate. Translations were performed from English to Arabic, to Hindi, to Gaelic, to Chinese

(traditional), to Russian and back to English.

Original text	*Text after translation*
1) Cut bacon into 1/4 inch thick pieces. Simmer bacon for 10 minutes in water. Drain and pat dry. Meanwhile, preheat oven to 450 degrees.	1) Cut the bacon into 1/4 inch slices. Bacon is boiled in water for 10 minutes. Moisten and let it dry. At the same time, preheat the oven to 450 degrees.
2) In a large casserole pot, saute bacon in olive oil on moderate heat for about 2-3 minutes to brown lightly. When ready, reserve bacon to a side dish.	2) In a large saucepan, bake olive oil over low heat for 2-3 minutes, until it turns slightly brown. When ready, put the bacon in the side dish.
3) Pat dry the cubed beef with paper towels and brown in olive oil in the same pot. Brown on all sides. Only do one layer at a time, so don't overcrowd the pot. Reserve meat to a plate when done.	3) Dry the chopped beef in a bowl with paper towels and brown olive oil. Brown from all sides. Just fold it once to avoid folding the pot. When done, store the meat on a plate.

The outcome is sometimes accurate, sometimes involves a loss of accuracy, and is occasionally meaningless or wrong. It is worth noting that technical terms such as "simmer" or "reserve" vanished.

What happened in this process? Google translate uses a Neural Machine Translation System that builds on preexisting translations to find statistical patterns (Wu et al., 2016). However, these statistical patterns do not always preserve meaning. A good translator does not just rely on usual ways to translate words and sentences but strives to convey meaning in another language. Here, conveying meaning is a practical notion; it means to enable the reader to perform the recipe. Since cooking methods and ingredients are specific to a locality, translating a recipe should not be literal; the translated text has to find its home in a different gastronomic culture.

There are many ways to convey meaning in translation. For example, the translator may choose not to translate a word but to define it instead. The recipe used here is itself a "human" translation from the french. However, in french, "reserve bacon to a side dish" is redundant because "réserver" means to keep aside for later use; this is an implicit definition. Similarly, translating ingredients is a very complex operation because it involves substitutions. Ultimately, sometimes, the only way to translate a recipe correctly involves tests to reproduce it in a given locality. The meaning of recipes stems from the coupling between a food production and distribution apparatus, and a culture of culinary techniques.

To convey the meaning of a text, good translators often need to depart from the text and *a fortioti* from its statistical translation. The statistical translations are the ones that maximize entropy, at least in a conceptual sense (sometimes in the technical sense of information theory), because they are the most probable output once we have a database of known translations. In other words, the automatic translations are the ones that fit the most closely to preexisting patterns. By contrast, the departing from the most probable translations by a good translator involves the choice of an unlikely translation to convey meaning. This notion fits our concept of novelty (Montévil, 2019b), thus corresponds to the concept of anti-entropy production transposed at the linguistic and gastronomic interface — let us recall that, here, cooking tests are part of the translator tools: translation is never just a linguistic problem.

In a nutshell, the preservation of meaning in translation often requires the introduction of novelties in the translation, akin to the production of biological anti-entropy. Like biological novelties, they are unlikely and, at the same time, convey a specific meaning. By contrast, the use of automatic statistical translations leads to a more or less significant loss of meaning because of its inability to introduce such novelties. In this perspective, translators do not optimize the transmission of information *sensu* Shannon (1948); instead, they add information to preserve the initial meaning.

Another interesting example is the interaction between infants and digital media. This interaction does not provide benefits and can be detrimental to children (Brown and et al, 2011). Let us quote part of the explanation given by Marcelli et al. (2018).

> The sequences presented to toddlers on screens have a double effect: the "show" in perpetual motion captures their eyes, but this capture takes place without any interactive synchrony with what these toddlers can feel, understand, live, experience, etc.

> They are passive and submissive spectators who go through the scenario and hear a "mechanical" voice, which, most often, makes them silent. Because there is no prosodic synchronization possible, the toddler remains silent ...

> [...] this flow of stimulation leaves the toddler in front of an attractive enigma but one that is difficult to understand. (Marcelli et al. 2018, we translate)

In a nutshell, young children are not able to follow a narrative by themselves. Parents "cheat" and adjust their proto-narrative to their children's behavior in order for this proto–narrative to make sense for the child. In other words, the parents constitute meaning artificially by improvisations based on infant reactions. This activity does not exist in the case of digital media, where the unfolding of the scenario is generic.

In both the case of translators and parents, we see that the ability to generate novelties is critical in order to convey or generate meaning. Here, novelties contribute to a specific meaning and are, at the same time, unlikely. They can be improbable but may also not even be possible in a positive sense. For example, words outside of the dictionary can be used, such as untranslated words or neologisms. In the use of current algorithms, the ability to generate such novelties disappears.

Are there similar phenomena in strictly biological situations? Templeton et al. (2001) raise the issue of the disruption of evolution, and more specifically of the process of adaptation by natural selection. If a population is fragmented, the gene flows between the different fragments stop, and the evolutionary processes will take place in each fragment independently. The population relevant to the evolutionary analysis shrinks from the initial population to the population of each fragment. Then the nature of the evolutionary dynamics changes. It becomes dominated by genetic drift, and each subpopulation's genetic diversity will decrease. The process of natural selection will not have enough diversity for differential reproduction to lead to adaptations. Empirical results support this analysis (Williams et al., 2003). Here, by contrast with the previous section, it is not only the result of a history that is the object of the disruption but also the ability to produce a history. The ability to produce anti-entropy by the process of natural selection is disrupted.

4   Conclusion

The concept of entropy requires rigorous reasoning; otherwise, it leads to significant mistakes. Entropy is a reliable concept in equilibrium thermodynamics. Since the

concept of usable energy depends on the couplings with a system's surroundings, and these couplings can be diverse to study the life cycle of a given artifact, it would make little sense to perform a straightforward accounting of physical entropy.

Non-equilibrium thermodynamics and theoretical biology are far from being as theoretically stable as equilibrium thermodynamics. Nevertheless, there are definite situations. Earth is an open system, where geological processes contingently magnify the concentration of elements leading to ore deposits formation. Once purified and used to construct artifacts, the use of these artifacts tends to disperse these resources back in the environment. It is especially the case in tire and breaks wear. Organisms may concentrate them again, with adverse consequences for both humankind and wildlife. Processes leading to the increase in the concentration of elements are associated with a cost in free energy in one form or another, they can happen spontaneously because Earth and the biosphere are far from thermodynamic equilibrium and are open to fluxes of energy.

The concept of entropy and its derivatives are necessary to address these phenomena and the notion of "consuming energy" and "consuming mineral resources". The core of this conceptual point is that, in both cases, configurations matter more than mere quantities. However, physical analyses are limited to the functioning of a machine or a given step in its production. However, what genuinely matters is their articulation with given biological, technological, and social organizations.

In biology, we have emphasized the centrality of organizations and their historical dimension. They lead to the concepts of anti-entropy and anti-entropy production. Anti-entropy corresponds to relevant parts of an organization that are the specific result of history, and perform a role in organizations because of that. Anti-entropy production is the appearance of a novelty in a strong sense: an outcome that was initially improbable or even unprestatable, and that provides a specific contribution to the organization. It follows that both concepts are relative to a given organization.

These two concepts lead to two kinds of disruption of biological and human organizations. In the disruption of anti-entropy, changes lead to the loss of specific configurations associated with a specific role in organizations. In other words, part of anti-entropy is lost in favor of more random configurations w.r. to the biological organization. This phenomenon is the entropization of part of anti-entropy.

The disruption of anti-entropy production is the loss of the ability to generate novelties contributing to biological organizations. In the human examples discussed, the ability to produce specific texts or interactions conveying meaning is disrupted by the use of digital media.

Overall, this investigation shows that the concept of entropy is critical to understand the Anthropocene; however, its specific role ultimately depends on the analysis of relevant physical processes and biological or social organizations.

Acknowledgments

References

Amiri, M. and M. M. Khonsari (2010). On the thermodynamics of friction and weara review. *Entropy*, 12(5):1021–1049. ISSN 1099-4300. doi: `10.3390/e12051021`.

Ayres, R. U. (1999). The second law, the fourth law, recycling and limits to growth. *Ecological Economics*, 29(3):473 – 483. ISSN 0921-8009. doi: `10.1016/S0921-8009(98)00098-6`.

Bailly, F. and G. Longo (2009). Biological organization and anti-entropy. *Journal of Biological Systems*, 17(1):63–96. doi: `10.1142/S0218339009002715`.

Balleza, E., E. R. Alvarez-Buylla, A. Chaos, S. Kauffman, I. Shmulevich, and M. Aldana (2008). Critical dynamics in genetic regulatory networks: Examples from four kingdoms. *PLoS ONE*, 3(6):e2456. doi: `10.1371/journal.pone.0002456`.

Barron, M. G. (2003). Bioaccumulation and bioconcentration in aquatic organisms. In D. J. Hoffman, B. A. Rattner, G. A. B. Jr., and J. C. Jr., editors, *Handbook of Ecotoxicology*, pages 877–892. Lewis Publishers, Boca Raton, Florida.

Basaran, C., M. Lin, and H. Ye (2003). A thermodynamic model for electrical current induced damage. *International Journal of Solids and Structures*, 40(26):7315 – 7327. ISSN 0020-7683. doi: `10.1016/j.ijsolstr.2003.08.018`.

van Bertalanffy, L. (2001). *General system theory: Foundations, development, applications*. Braziller.

Bertolotti, T. and L. Magnani (2017). Theoretical considerations on cognitive niche construction. *Synthese*, 194(12):4757–4779. ISSN 1573-0964. doi: `10.1007/s11229-016-1165-2`.

Bich, L. and G. Bocchi (2012). Emergent processes as generation of discontinuities. In *Methods, models, simulations and approaches towards a general theory of change.*, pages 135–146. World Scientific, Singapore. doi: `10.1142/9789814383332_0009`.

Braun, E. (2015). The unforeseen challenge: from genotype-to-phenotype in cell populations. *Reports on Progress in Physics*, 78(3):036602. doi: `10.1088/0034-4885/78/3/036602`.

Brown, A. and et al (2011). Media use by children younger than 2 years. *Pediatrics*, 128(5):1040–1045. ISSN 0031-4005. doi: `10.1542/peds.2011-1753`.

Browne, M. A., P. Crump, S. J. Niven, E. Teuten, A. Tonkin, T. Galloway, et al. (2011). Accumulation of microplastic on shorelines woldwide: Sources and sinks. *Environmental Science & Technology*, 45(21):9175–9179. doi: `10.1021/es201811s`. PMID: 21894925.

Bryant, M., M. Khonsari, and F. Ling (2008). On the thermodynamics of degradation. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 464(2096):2001–2014. doi: `10.1098/rspa.2007.0371`.

Buonsante, P., R. Franzosi, and A. Smerzi (2016). On the dispute between boltzmann and gibbs entropy. *Annals of Physics*, 375:414 – 434. ISSN 0003-4916. doi: `10.1016/j.aop.2016.10.017`.

Chibbaro, S., L. Rondoni, and A. Vulpiani (2014). *Reductionism, Emergence and levels of reality.* Springer. ISBN 978-3-319-06361-4. doi: `10.1007/978-3-319-06361-4`.

Corre, G., D. Stockholm, O. Arnaud, G. Kaneko, J. Viñuelas, Y. Yamagata, et al. (2014). Stochastic fluctuations and distributed control of gene expression impact cellular memory. *PLOS ONE*, 9(12):1–22. doi: `10.1371/journal.pone.0115574`.

Dadachova, E., R. A. Bryan, X. Huang, T. Moadel, A. D. Schweitzer, P. Aisen, et al. (2007). Ionizing radiation changes the electronic properties of melanin and enhances the growth of melanized fungi. *PLOS ONE*, 2(5):1–13. doi: `10.1371/journal.pone.0000457`.

David, L., Y. Ben-Harosh, E. Stolovicki, L. S. Moore, M. Nguyen, R. Tamse, et al. (2013). Multiple genomic changes associated with reorganization of gene regulation and adaptation in yeast. *Molecular Biology and Evolution*, 30(7):1514–1526. doi: `10.1093/molbev/mst071`.

Davis, J., A. A. Moulton, L. Van Sant, and B. Williams (2019). Anthropocene, capitalocene, plantationocene?: A manifesto for ecological justice in an age of global crises. *Geography Compass*, 13(5):e12438. doi: `10.1111/gec3.12438`. E12438 GECO-1180.R1.

D.Scott, S., H. D. Holland, and K. K. Turekian, editors (2014). *Geochemistry of Mineral Deposits*, *Treatise on Geochemistry*, volume 13. Elsevier, Oxford, 2 edition. ISBN 978-0-08-098300-4.

Gatti, R. C., B. Fath, W. Hordijk, S. Kauffman, and R. Ulanowicz (2018). Niche emergence as an autocatalytic process in the evolution of ecosystems. *Journal of Theoretical Biology*, 454:110 – 117. ISSN 0022-5193. doi: `10.1016/j.jtbi.2018.05.038`.

Gayon, J. and M. Montévil (2017). *Repetition and Reversibility in Evolution: Theoretical Population Genetics*, pages 275–314. Springer International Publishing, Cham. ISBN 978-3-319-53725-2. doi: `10.1007/978-3-319-53725-2_13`.

Georgescu-Roegen, N. (1993). The entropy law and the economic problem. In *Valuing the Earth: Economics, ecology, ethics*, pages 75–88. MIT Press Cambridge, MA.

Goldstein, S., J. L. Lebowitz, R. Tumulka, and N. Zanghi (2019). Gibbs and boltzmann entropy in classical and quantum mechanics. *arXiv preprint arXiv:1903.11870*.

Haraway, D. (2015). Anthropocene, Capitalocene, Plantationocene, Chthulucene: Making Kin. *Environmental Humanities*, 6(1):159–165. ISSN 2201-1919. doi: `10.1215/22011919-3615934`.

Heinrich, C. and P. Candela (2014). *Fluids and Ore Formation in the Earth's Crust*, *Treatise on Geochemistry*, volume 13: Geochemistry of Mineral Deposits, chapter 1, pages 1 – 28. Elsevier, Oxford, 2 edition. ISBN 978-0-08-098300-4. doi: `10.1016/B978-0-08-095975-7.01101-3`.

Jane, M., C. P. G., W. N. M., and P. M. V. (2007). Global warming and the disruption of plantpollinator interactions. *Ecology Letters*, 10(8):710–717. doi: `10.1111/j.1461-0248.2007.01061.x`.

Kaern, M., T. C. Elston, W. J. Blake, and J. J. Collins (2005). Stochasticity in gene expression: from theories to phenotypes. *Nature Reviews Genetics*, 6(6):451–464. doi: `10.1038/nrg1615`.

Kauffman, S. (2002). *Investigations.* Oxford University Press, USA, New York. ISBN 9780195121056.

Kauffman, S. A. (1993). *The origins of order: Self organization and selection in evolution.* Oxford University Press, New York.

Kauffman, S. A. (2019). *A World Beyond Physics: The Emergence and Evolution of Life.* Oxford University Press, New York.

Kirchhoff, M., T. Parr, E. Palacios, K. Friston, and J. Kiverstein (2018). The markov blankets of life: autonomy, active inference and the free energy principle. *Journal of The Royal Society Interface*, 15(138):20170792. doi: `10.1098/rsif.2017.0792`.

Kupiec, J. (1983). A probabilistic theory of cell differentiation, embryonic mortality and dna c-value paradox. *Specul. Sci. Techno.*, 6:471–478.

Lestas, I., G. Vinnicombe, and J. Paulsson (2010). Fundamental limits on the suppression of molecular fluctuations. *Nature*, 467:174 EP –. doi: `10.1038/nature09333`.

Letelier, J. C., G. Marin, and J. Mpodozis (2003). Autopoietic and (m,r) systems. *Journal of Theoretical Biology*, 222(2):261 – 272. ISSN 0022-5193. doi: `10.1016/S0022-5193(03)00034-1`.

Longo, G. (2018). How future depends on past and rare events in systems of life. *Foundations of Science*, 23(3):443–474. ISSN 1572-8471. doi: `10.1007/s10699-017-9535-x`.

Longo, G., M. Montevil, C. Sonnenschein, and A. M. Soto (2015). In search of principles for a theory of organisms. *Journal of biosciences*, 40(5):955–968. ISSN 0973-7138. doi: `10.1007/s12038-015-9574-9`. 26648040[pmid].

Longo, G. and M. Montévil (2014a). Biological order as a consequence of randomness: Anti-entropy and symmetry changes. In *Perspectives on Organisms*, Lecture Notes in Morphogenesis, pages 215–248. Springer Berlin Heidelberg. ISBN 978-3-642-35937-8. doi: `10.1007/978-3-642-35938-5_9`.

Longo, G. and M. Montévil (2014b). *Perspectives on Organisms: Biological time, symmetries and singularities.* Lecture Notes in Morphogenesis. Springer, Heidelberg. ISBN 978-3-642-35937-8. doi: `10.1007/978-3-642-35938-5`.

Longo, G., M. Montévil, and S. Kauffman (2012). No entailing laws, but enablement in the evolution of the biosphere. In *Genetic and Evolutionary Computation Conference.* GECCO12, ACM, New York, NY, USA. doi: `10.1145/2330784.2330946`.

Lotka, A. J. (1945). The law of evolution as a maximal principle. *Human Biology*, 17(3):167–194.

Maher, K. and R. Yazami (2014). A study of lithium ion batteries cycle aging by thermodynamics techniques. *Journal of Power Sources*, 247:527 – 533. ISSN 0378-7753. doi: `10.1016/j.jpowsour.2013.08.053`.

Marcelli, D., M.-C. Bossière, and A.-L. Ducanda (2018). Plaidoyer pour un nouveau syndrome ń exposition précoce et excessive aux écrans ż (epee). *Enfances & Psy*, 79(3):142–160. doi: `10.3917/ep.079.0142`.

Meyerovich, M., G. Mamou, and S. Ben-Yehuda (2010). Visualizing high error levels during gene expression in living bacterial cells. *Proceedings of the National Academy of Sciences of the United States of America*, 107(25):11543–11548. ISSN 1091-6490. doi: `10.1073/pnas.0912989107`. PMC2895060[pmcid].

Miquel, P.-A. and S.-Y. Hwang (2016). From physical to biological individuation. *Progress in Biophysics and Molecular Biology*, 122(1):51 – 57. ISSN 0079-6107. doi: `10.1016/j.pbiomolbio.2016.07.002`.

Montévil, M. (2019a). Measurement in biology is methodized by theory. *Biology & Philosophy*, 34(3):35. ISSN 1572-8404. doi: `10.1007/s10539-019-9687-x`.

Montévil, M. (2019b). Possibility spaces and the notion of novelty: from music to biology. *Synthese*, 196(11):4555–4581. ISSN 1573-0964. doi: `10.1007/s11229-017-1668-5`.

Montévil, M. (2019c). Which first principles for mathematical modelling in biology? *Rendiconti di Matematica e delle sue Applicazioni*, 40:177–189.

Montévil, M. and M. Mossio (2015). Biological organisation as closure of constraints. *Journal of Theoretical Biology*, 372:179 – 191. ISSN 0022-5193. doi: `10.1016/j.jtbi.2015.02.029`.

Montévil, M., M. Mossio, A. Pocheville, and G. Longo (2016). Theoretical principles for biology: Variation. *Progress in Biophysics and Molecular Biology*, 122(1):36 – 50. ISSN 0079-6107. doi: `10.1016/j.pbiomolbio.2016.08.005`.

Moore, J. W., editor (2016). *Anthropocene or Capitalocene? Nature, History, and the Crisis of Capitalism*. PM Press.

Mora, T. and W. Bialek (2011). Are biological systems poised at criticality? *Journal of Statistical Physics*, 144:268–302. ISSN 0022-4715. doi: `10.1007/s10955-011-0229-4`.

Morellato, L. P. C., B. Alberton, S. T. Alvarado, B. Borges, E. Buisson, M. G. G. Camargo, et al. (2016). Linking plant phenology to conservation biology. *Biological Conservation*, 195:60 – 72. ISSN 0006-3207. doi: `10.1016/j.biocon.2015.12.033`.

Mosseri, R. and J. Catherine, editors (2013). *L'énergie à découvert*. CNRS Éditions, Paris.

Mossio, M., M. Montévil, and G. Longo (2016). Theoretical principles for biology: Organization. *Progress in Biophysics and Molecular Biology*, 122(1):24 – 35. ISSN 0079-6107. doi: `10.1016/j.pbiomolbio.2016.07.005`.

Nicolis, G. and I. Prigogine (1977). *Self-organization in non-equilibrium systems*. Wiley, New York.

Odling-Smee, F. J., K. N. Laland, and M. W. Feldman (2003). *Niche construction: the neglected process in evolution*. Princeton University Press. ISBN 9780691044378.

Pocheville, A. (2010). *What niche construction is (not).*

Rafferty, N. E., P. J. CaraDonna, and J. L. Bronstein (2015). Phenological shifts and the fate of mutualisms. *Oikos*, 124(1):14–21. doi: `10.1111/oik.01523`.

Ripple, W. J., C. Wolf, T. M. Newsome, M. Galetti, M. Alamgir, E. Crist, et al. (2017). World scientists warning to humanity: A second notice. *BioScience*, 67(12):1026–1028. doi: `10.1093/biosci/bix125`.

Robbirt, K., D. Roberts, M. Hutchings, and A. Davy (2014). Potential disruption of pollination in a sexually deceptive orchid by climatic change. *Current Biology*, 24(23):2845 – 2849. ISSN 0960-9822. doi: `10.1016/j.cub.2014.10.033`.

Rogge, W. F., L. M. Hildemann, M. A. Mazurek, G. R. Cass, and B. R. T. Simoneit (1993). Sources of fine organic aerosol. 3. road dust, tire debris, and organometallic brake lining dust: roads as sources and sinks. *Environmental Science & Technology*, 27(9):1892–1904. doi: `10.1021/es00046a019`.

Rosen, R. (1991). *Life itself: a comprehensive inquiry into the nature, origin, and fabrication of life.* Columbia University Press, New York.

Rovelli, C. (2017). *Is Time's Arrow Perspectival?*, page 285296. Cambridge University Press. doi: `10.1017/9781316535783.015`.

Schrödinger, E. (1944). *What Is Life?* Cambridge University Press, Londre.

Sethna, J. P. (2006). *Statistical mechanics: Entropy, order parameters, and complexity.* Oxford University Press, New York. ISBN 0198566778.

Shannon, C. E. (1948). A mathematical theory of communication. *The Bell System Technical Journal*, 27:379423.

Soto, A. M., G. Longo, D. Noble, N. Perret, M. Montévil, C. Sonnenschein, et al. (2016). From the century of the genome to the century of the organism: New theoretical approaches. *Progress in Biophysics and Molecular Biology, Special issue*, pages 1–82.

Soto, A. M., C. Sonnenschein, and P.-A. Miquel (2008). On physicalism and downward causation in developmental and cancer biology. *Acta Biotheoretica*, 56(4):257–274. doi: `10.1007/s10441-008-9052-y`.

Stevenson, T. J., M. E. Visser, W. Arnold, P. Barrett, S. Biello, A. Dawson, et al. (2015). Disrupted seasonal biology impacts health, food security and ecosystems. *Proc Biol Sci*, 282(1817):20151453–20151453. ISSN 1471-2954. doi: `10.1098/rspb.2015.1453`.

Stiegler, B. (2018). *The neganthropocene.* Open Humanites Press.

do Sul, J. A. I. and M. F. Costa (2014). The present and future of microplastic pollution in the marine environment. *Environmental Pollution*, 185:352 – 364. ISSN 0269-7491. doi: `10.1016/j.envpol.2013.10.036`.

Templeton, A. R., R. J. Robertson, J. Brisson, and J. Strasburg (2001). Disrupting evolutionary processes: The effect of habitat fragmentation on collared lizards in the missouri ozarks. *Proceedings of the National Academy of Sciences*, 98(10):5426–5432. ISSN 0027-8424. doi: `10.1073/pnas.091093098`.

Turing, A. M. (1952). The chemical basis of morphogenesis. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, 237(641):37–72. doi: `10.1098/rstb.1952.0012`.

Varela, F., H. Maturana, and R. Uribe (1974). Autopoiesis: The organization of living systems, its characterization and a model. *Biosystems*, 5(4):187 – 196. ISSN 0303-2647. doi: `10.1016/0303-2647(74)90031-8`.

Visser, M., S. Caro, K. Van Oers, S. Schaper, and B. Helm (2010). Phenology, seasonal timing and circannual rhythms: towards a unified framework. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365(1555):3113–3127. doi: `10.1098/rstb.2010.0111`.

Williams, B. L., J. D. Brawn, and K. N. Paige (2003). Landscape scale genetic effects of habitat fragmentation on a high gene flow species: Speyeria idalia (nymphalidae). *Molecular Ecology*, 12(1):11–20. doi: `10.1046/j.1365-294X.2003.01700.x`.

Wu, Y., M. Schuster, Z. Chen, Q. V. Le, M. Norouzi, W. Macherey, et al. (2016). Google's neural machine translation system: Bridging the gap between human and machine translation. *CoRR*, abs/1609.08144.

Young, J. T. (1991). Is the entropy law relevant to the economics of natural resource scarcity? *Journal of Environmental Economics and Management*, 21(2):169 – 179. ISSN 0095-0696. doi: `10.1016/0095-0696(91)90040-P`.

Zoeller, R. T., T. R. Brown, L. L. Doan, A. C. Gore, N. E. Skakkebaek, A. M. Soto, et al. (2012). Endocrine-disrupting chemicals and public health protection: A statement of principles from the endocrine society. *Endocrinology*, 153(9):4097–4110. doi: `10.1210/en.2012-1422`.