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Evolution, Through the Lens of a Physicist

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Abstract

With the following considerations, the author intends to enrich the discussion about chance and the formation of new organisms in biological evolution. As a physicist, he knows that he has already crossed a boundary of disciplines by discussing the occurrence of chance. The natural scientist or biologist leaves the field of natural science to enter the world of ideas, humanities, and metaphysics. A second argument considers the relation between the whole and its parts. Decomposing biological systems to the smallest building blocks (molecules and atoms) does not mean the whole can be constructed from these particles without additional causal agents. This may indicate that the evolutionary process may involve more than changes in a DNA string.

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1. Introduction

In 2009, it was 150 years since Darwin published his groundbreaking study on the Origin of Species [Darwin 1859]. Darwin's work has profoundly influenced biology, providing a unified understanding of various facts and phenomena. It's not just instrumental in explaining the remarkable consistency in the biological building blocks, such as the cell with its DNA and the organic structures across all animal classes. It also illuminates the historical evolution of DNA and its relationship with fossil data. Darwin's work is a cornerstone of modern biology, a robust and substantiated theory that has shaped our understanding of life on Earth.

The Darwin year was for Driessen and Nienhuis [Driessen 2010a], an opportunity to edit a collection “Evolution, scientific model or secular belief”. The main idea was that evolution appears to have a double meaning. Primarily, it is a widely accepted theory that has led to a deeper understanding of the scientific findings of biology. For many, evolution also includes the general background of this scientific theory. The latter may lead to controversies as the scientific data and results do not enforce a unique general background. The Jewish, Muslim, and Christian believers in [Driessen 2010a] all accept the scientific theory of evolution. However, the general background of these authors is quite different from each other.

The contribution in [Driessen 2010b] considered evolution as seen with the general background of a physicist. A few years later, the author investigated the intersection of biology and quantum mechanics [Driessen 2015]. These considerations were inspired by Aristotelian hylomorphism. In the present study, the author extends his previous considerations of evolution by focusing mainly on the concept of chance and the wholeness of biological systems.

One may ask what a physicist could add to a better understanding of evolution. First and foremost, a physicist should express profound respect for the work of his colleagues in biology. A physicist is used to reduce everything to relatively simple systems. Only these are accessible to the currently available experimental and theoretical methods. In biology, however, it is not just about highly complex structures like those studied in chemistry. Instead, it is mainly about the function of these structures. Consider, for example, growth based on cell division or reproduction by joining egg and sperm. The study of biological objects requires the development of its peculiar theories and methods. Biology is not just applied chemistry, and this, in turn, is not only applied physics.

Nevertheless, a physicist may well contribute to the development of biological science. For example, one might expect fundamental laws such as the law of gravity to apply to biological objects just as they would to a bucket of water or sand. In this respect, physics provides a framework within which biological laws are valid. Similarly, in the area of fundamental questions in the field of science theory, insights from physics can be illuminating for biology. Every natural science discipline has a general background, an upper layer, that systematically considers logical and methodical assumptions. Since Aristotle, the upper layer of physics has been called metaphysics, i.e., that which comes after physics. It now appears that the upper layer relates to the science in the lower layer but partly belongs to a different discipline, namely philosophy. The upper layer, the general background, of an area of science (physics or biology) includes natural science, Geisteswissenschaft, and humanities. In analogy to physics and metaphysics, one could also distinguish between biology as a scientific discipline and the upper layer of biology, metabiology. At that level, the researcher reflects on the scientific results with a view that includes philosophical and mathematical concepts underlying biology [Carsetti 2020].

It is impossible to define the boundary between the lower and upper layers in all details, but it does exist. It is an ever-present temptation to regard one's field as normative or decisive for all areas of science. A more explicit warning about the need to recognize the limit to one's particular field comes from Louis De Broglie, one of the founders of quantum mechanics and a Nobel laureate. He wrote [De Broglie 1947]:

> *We want to show that science, as it develops, is necessarily led to introduce into its theories concepts with a metaphysical scope, such as those of time, space, objectivity, causality, individuality, etc..... Science seeks to give precise definitions of these concepts within the framework of the methods it employs and to avoid any philosophical discussion of them; perhaps, in so doing, it often engages in metaphysics without admitting it, which is not the least dangerous way of doing so.*

It does not mean, of course, that the physicist or biologist should not reflect on the foundations and implications of his discipline. It is undoubtedly necessary, but it should be done with the attitude of a philosopher of science, with the corresponding methods and concepts.

In the following, two cases will elaborate on these abstract considerations. Physics has the advantage of dealing with fundamental laws of science where the connection with metaphysics is more worked out than in biology. The first case concerns the concepts of chance and purpose, or in the words of Jacques Monod, chance and necessity [Monod 1971]. The question will be whether a physicist can confirm or exclude the occurrence of chance in an event with his methods. If this is not possible, as shown below, serious doubts could arise about whether a biologist could do so. The second example investigates one of the fundamental philosophical issues: whether the whole is more than the sum of its parts. It appears that there is strong theoretical and experimental evidence in physics that confirms this. The concept of reductionism that often occurs in science demands the necessary nuances. The discussion in the last section will pick up the story's thread and examine what the considerations may mean for biology, specifically for the theory of evolution.

2. Can a physicist distinguish between chance and purpose?

In his book *The Idea of Chance in the Thought of Charles Darwin*, Curtis Johnson presents a summary of the theory of Darwin [Johnson 2015, p. xiv-xv]:

> *step 1: Variation*
>
> *All creatures that reproduce will produce offspring that vary slightly from themselves. (….) Darwin could often do not better than to say that any variation from parent to child is due to what we must, in our ignorance, call chance.*
>
> *step 2: Heritability*
>
> *Variations are often passed along in reproduction. (…) Variations often have a tendency to be preserved.*
>
> *step 3: Competition for survival*
>
> *More creatures are born in every species or group than can normally survive. (…) Only the few ever survive. This phenomenon came to be called by Darwin “survival of the fittest”.*
>
> *step 4: Natural selection*
>
> *This principle determines who are the winners and losers in the perpetual struggle for existence. Those creatures that have varied in “favorable” directions are more likely to survive than thoses that have not varied, or have varied in unfavourable ways. (…) Darwin did not claim to know how or why some individuals happened to vary but only that if they did vary in favourable direction, they had a better chance to be selected for survival than ones that did not vary.*

In steps 1 and 4, evolution's “chancy” nature appears explicitly. Ramsey and Pent explain [Ramsey 2016, p 2]:

> *Chance is taken (…) to be central to the understanding of fitness, genetic drift, macroevolution, mutation, foraging theory, and environmental variation, to mention but a few examples.*

Speaking about chance, one should acknowledge the landmark contribution of Jacques L. Monod: Chance and Necessity: an Essay on the Natural Philosophy of Modern Biology [Monod 1971]. He summarizes his findings in the last paragraph:

> *The ancient covenant is in pieces; man knows at last that he is alone in the universe's unfeeling immensity, out of which he emerged only by chance. His destiny is nowhere spelled out, nor is his duty. The kingdom above or the darkness below; it is for him to choose”*

One of our conclusions will be that only the philosopher, not the scientist, may provide arguments for the correctness of this statement.

If chance plays such an essential role in the theory of evolution, what can be said about the related concept of purpose? If one uses the term design instead of purpose, one immediately sees that physicists' thoughts on this term certainly have meaning for a biologist. The question is whether referring to chance is a scientific conclusion of a scientist or the result of considerations at the meta-level. Is there a scientific method or procedure for demonstrating or ruling out one of these alternatives?

An expression attributed to Galilei states that the language of science is mathematics. Therefore, the relation between mathematics and chance is relevant to our argument. One could, as an example, propose the question about purpose or chance to a mathematician or an information scientist and investigate random numbers. These are well-known in mathematics, but there is no algorithm or pure mathematical procedure to generate them. When a computer produces random numbers, it is sufficiently random for many applications. However, one may observe non-randomness in pseudo-random number bitmaps by visual inspecting. To illustrate the situation, Bo Allen compares the outcome of a true random number generator based on a quantum mechanical device and a computer-generated pseudo-random number generator. Just by visual inspection of the resulting bitmaps, a non-random pattern becomes visible in the pseudo-random outcome [Allen 2023]; see also [Mulder 2023].

Also, the inverse is true. If one considers the experiment with throwing coins, no mathematical algorithms can differentiate between a random or nonrandom series even after millions of throws. We conclude that mathematical tools cannot grasp chance or design unless we declare an event as being random if the mathematical algorithms that could account for it exceed an arbitrarily defined complexity limit. In that case, it is not mathematics but a human subject that ultimately determines whether the complexity is such that one may speak of a random event.

Since the early days of Quantum mechanics (QM) about a century ago, we know that the laws of physics for the microscopic scale have a statistical character. A single event can be predicted only by a certain degree of probability. The reason for this is not the lack of information regarding the system but the inherent indeterminism of the natural laws of QM. Introducing unknown parameters in the description of the event, such as hidden variables, does not solve the problem. According to Bell, experiments can sometimes distinguish between a QM or hidden variable approach [Mermin 1993]. In all cases, the statistical character of the laws of QM is confirmed.

In one of his lectures, John Bell [1997] used an explicit way to explore the role of chance and intent. He designed a Gedankenexperiment in which perfect coins are tossed, where each toss showed a head or tail with equal likelihood. This is a perfect analog of a quantum mechanical system that can get into one of two possible final states with equal probability. He generated a series of outcomes using a computer's random number generator. He visualized them in a graph, placing an H for head and a space for tail, see Fig. 1. He then introduced a magical force that secretly flipped some of the coins one more time after the toss in the inverted image of Fig. 1. He thereby obtained Fig. 2. To a physicist, both images are ordinary graphic representations of an experimental observation of a probability process. If one overlays the two images, see Figure 3, the letters EPR emerge with a nod to the famous article by Einstein, Podolski, and Rosen [Einstein 1935]. What can one conclude from this? Two representations of a purely random process contain together a structure that is not at all random. It should be added that the result of Figure 3 may be just as accidental or intended for a physicist as either Fig. 1 or 2. There is simply no physical procedure or device to demonstrate or rule out the intent of the magical force in Fig. 2.

What does this mean? We are entering a meta-level because the letter combination EPR is only salient at that level, not at the level of pure science. It means that conclusions about intent, intentionality, and design are not in the domain of the natural sciences. The same can be said about the absence. All that can be said is whether intentionality or its absence is probable. Within his discipline, a physicist is blind to recognizing and proving chance or intent.

Now, back to biological systems. Aren't these in general macroscopic systems, where classical physics provides an adequate description? It turns out that the fundamental processes in biological systems rely on QM. Kim et al. [2021] state:

> *Biology has traditionally been considered to belong to the classical domain, while physics and chemistry are deeply entrenched in quantum mechanics. Yet, living systems are fundamentally quantum mechanical since the dynamics of their molecular, atomic and subatomic chemical machinery is, like everything else, governed by the law of quantum physics.*

A distinction is made between trivial and non-trivial quantum effects, where the latter refers to*phenomena that are normally canceled out at the macroscopic level due to decoherence*. [Kim 2021]. Trivial quantum effects include fundamental processes of mutations, especially radiation-induced mutations [Ma 2021]. Mutations are not canceled at the macroscopic level, as each change in the DNA code may directly affect the next generation. In our discussion about Darwin's view on mutations, we safely may conclude that quantum statistics play a dominant role. If one goes up to the scale of molecular biology, then statistical properties are also expected to be observed in the form of noise [Blake 2003]. Here, too, the statistical laws of QM play a decisive role.

One may conclude that nondeterministic laws determine the outcome of many processes responsible for the four steps in evolution, as mentioned above. The biologist lacks, equally to the physicist, a tool to decide whether a given step in evolution is chance or intentional. Of course, the distinction can be made at the level of metascience. But now, it is not the scientist who decides but the scholar who reflects on scientific facts and draws certain conclusions.

3. Is the whole more than the sum of its parts, or what is life?

It is a fact that biological tissue engineering, starting exclusively from chemical compounds, is currently not possible [Tang 2020]. Life in all its manifestations, from the most primitive, such as a virus, to the higher levels of flora and fauna, remains beyond the engineer's capacity. Some believe it is a matter of time before science will be able to explain life and even be able to reproduce biological processes. To get that far, one must unravel the chemical processes and study the underlying physical phenomena in detail. In this view, biology becomes applied chemistry, which can be thought to be applied physics. Others prefer a holistic view and consider the living matter something that cannot be reduced to inanimate blocks.

Not only scientists are concerned with the fundamental aspects of life. Philosophers have also developed deep thoughts about life since ancient Greece; see, e.g., [Driessen 2015]. When comparing with live-less matter, Aristotle concluded that a new level of information is present in living things. The name organism already indicates the presence of a structure consisting of parts with different functions. This information (form in philosophical jargon) is responsible not only for the living being as it is but also for its behavior and further development over time. This includes growth and recovery from injury as well as reproduction.

With Democritus, the founder of atomism and, in a sense, a precursor of Aristotle, the information in things was limited to the geometric pattern in which the tiny particles were arranged. These particles, which he called atoms, were all equal to each other and non-divisible (hence the name atom, Greek for non-divisible). With this model, Democritus makes it plausible that all things known can ultimately be reduced to elementary particles. But no justice is done here to the strong unity in living things. A division of a stone yields two stones; the division of a mammal, such as a dog, yields something entirely new, namely the two parts of a dead animal.

Reductionism is widespread among scientists. The whole is no more than the sum of its parts. That we are even now forced to consider the whole separately is only the result of the currently deficient state of science. Everything, including plants, animals, and man, is an aggregation of elementary particles with a specific arrangement. The vision of Descartes in the 17th century is well known. For him, living beings were complex machines, like a watch [Descartes 1642]. For many, this is shocking, yet it is an important observation. When we analyze the body of a living being, for example, a human being, we ultimately find nothing but what we know of lifeless matter. The laws of physics are as valid for the engineer as they are for the biologist and physician. This observation alone cannot explain the full spectrum of biological phenomena, but it excludes certain forms of vitalism [Kirschner 2000]. In that view, certain nonphysical elements distinguish living systems from the lifeless world.

The theoretical physicist and Nobel Prize winner P.W. Anderson brought forward an argument directly related to our problem. He distinguishes between the path from the complex system to the parts (reductionism) and the reverse path from the parts to the whole (constructionism). He writes [Anderson 1972]:

> *The reductionist hypothesis does not by any means imply a "constructionist" one: The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe.*

He accepts the reductionist's thesis without ruling out that the whole is subject to new laws that appear only at the higher level. With examples of his professional expertise, he illustrates that with increasing scale and complexity, a shift can be found from quantitative to qualitative changes. This means that in physics, even relatively simple systems cannot be understood in terms of the laws and properties of the constituent parts. New properties emerge in the higher system; for details, see [Butterfield 2011] and [Driessen 2016].

The examples mentioned by Anderson cannot be understood within classical physics. Concepts from QM, such as superposition and entanglement, play an important role here. Related phenomena such as superconductivity, superfluidity, and photon entanglement have been known for many decades and have been intensively studied with a view to promising applications. It is not the intention to discuss these examples in more detail here. However, one should note that even in relatively simple systems of inanimate nature, new laws come into play that cannot be applied to the individual parts. However, if one starts dissecting the whole, one finds only the parts with their well-known behavior according to reductionism.

In biology, reductionism is evident. In investigating living matter, one may find organs built of cells with the DNA helix. Further dividing leads to molecules and eventually to atoms and elementary particles. Reconstructing the molecules, DNA helix, cells, organs, and complete organisms is more challenging [Smith 1997]. If evolution acts by mutations of the building blocks of the DNA helix, then not all is said about the organism arising from the changed genetic material. It could be that besides the changed DNA, other natural laws or causes will contribute to the emergence of new biological systems [Brown 2023] [Jablonka 2014]. Gerd Muller proposes an extended evolutionary synthesis and writes [Müller 2017]

> *Whereas the modern synthesis of the 1940's and its various amendments concentrate on genetic and adaptive variation in populations, the extended framework emphasizes the role of constructive processes, ecological interactions and systems dynamics in the evolution of organismal complexity as well as its social and cultural conditions. Single-level and unilinear causation is replaced by multilevel and reciprocal causation.*

In this context, one should also mention adaptive phenotype plasticity that allows organisms to cope with various environments [Snell-Rood 2016].

4. Discussion

After the considerations in the two previous sections, it is time to pick up the introduction thread. The point was to consider whether physicists can make relevant contributions to a better understanding of evolution with the results of their discipline. At the same time, a comparison with physics and metaphysics would allow a sharper separation between evolution as science and evolution as a philosophical worldview (metabiology). The great challenge here is to arrive at a view that considers both the substantial unity of living organisms and the laws of inanimate nature, which are also valid in living matter.

Section 2 examined the ability of a physicist's methods to distinguish chance or intent. It turned out that the statistical nature of the laws of nature on a microscopic scale makes this distinction fundamentally impossible. It is expected that biologists also miss the tools to make this distinction. In any case, no well-founded claim in the literature is known to the author. This consideration leads to an important conclusion: If a biologist believes that in the biological objects, a designer or even a creator becomes visible, he cannot invoke the natural sciences. Such a statement is not that of a natural scientist but of a humanities practitioner or someone expressing his deep convictions. The same must be said when it is claimed with equal emphasis that everything is chance and nothing more; see, e.g., the quotation of Monod in section 2. Here again, the natural scientist does not speak. Both statements about the occurrence or exclusion of chance belong to the meta-level, in which natural science facts are analyzed within a particular metaphysics or worldview. It is not possible to speak about chance without referring to the meta-level. An example from physics, superdeterminisme, illustrates that the same physical laws lead to a completely different meta-level [Hossenfelder 2020]. Similar to the situation in physics in the first half of the last century, today, physicists or biologists *engage in metaphysics without admitting it*[De Broglie 1947]. The facts and scientific results do not imply a unique philosophical system. As the discussion of randomness intended to show, there is no ‘neutral’ science without referring to a specific meta-level.

The other issue discussed in the third section was the relationship between the whole and its parts. If the whole can be obtained by purely geometrically arranging the parts, then evolution from the simple to the complex could be somewhat insightful. Indeed, changes to the spatial distribution of the parts could sooner or later lead to a new complex whole. But in that picture, the embarrassing organic unity of the higher living beings remains completely underexposed. According to Anderson's view, however, one must look at the transition from the parts to the whole more nuancedly. It turns out that even in relatively simple systems, the whole cannot be constructed out of only the parts and the accompanying laws. Therefore, it is expected that the most complex systems, the living beings, cannot be built solely from the parts and the accompanying laws.

As a final illustration, consider Feuerbach's challenging statement,*Der Mensch ist, was er ißt*(man is what he eats) [Feuerbach 1850]. There is no problem with the reductionist view that all of man’s components could originally be found in his food. In the view of many, however, a human person can not be constructed exclusively from food. Science also would put question marks, as something new is expected in building the highly complex organism of man.

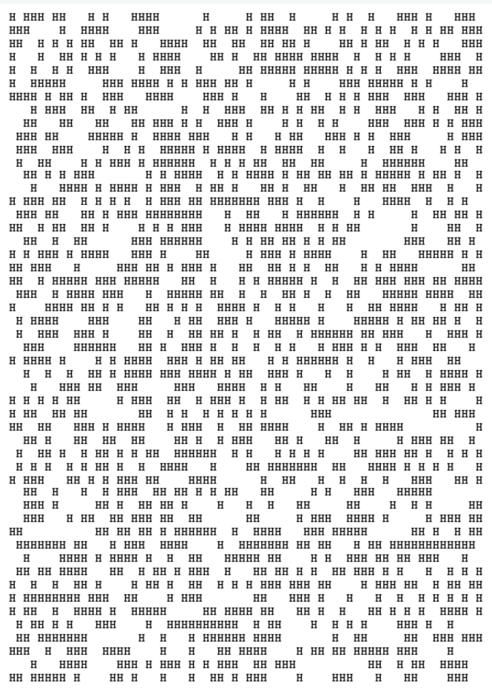

Fig. 1. *Result of computer simulation of a random series of heads 'H' and tails (blank)*

+

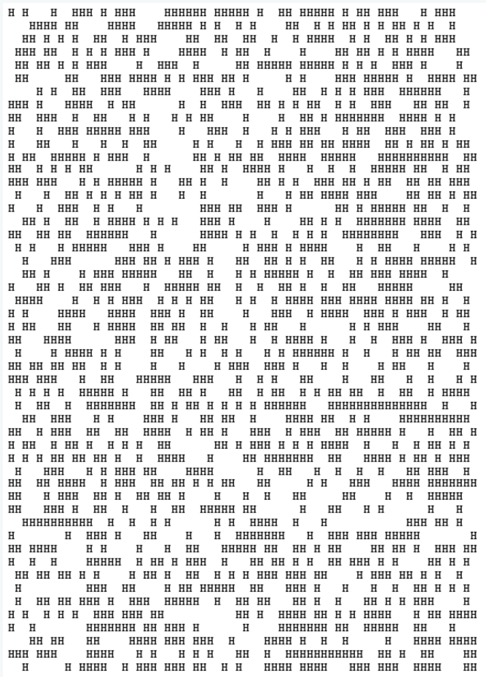

Fig. 2. *Inverted display of Fig.2: heads (blank), tails 'H'. The random code is changed in some places*

=

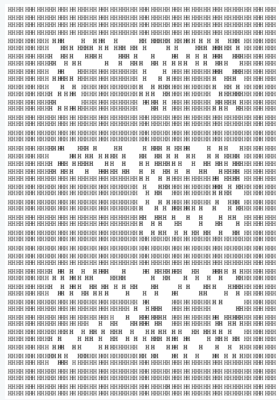

Fig. 3. *Superposed images of Figs. 1 and 2 (after B. Julesz)*

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Literature

- [Allen 2023] Allen, Bo, Pseudo-Random vs. True Random, A Simple Visual Example,https://boallen.com/random-numbers.html.
- [Anderson 1972] Anderson, P.W., *More is different*, Science 177, pp 393-396.
- [Bell 1997] Bell, John S., *Indeterminism and Nonlocality*, in Driessen, Alfred and Suarez, Antoine (Eds) *Mathematical Undecidability, Quantum Nonlocality and the Question of the Existence of God,* Springer (Kluwer).
- [Blake 2003] Blake, William J., Kaern, Mads, Cantor, Charles R., Collins, J.J.*Noise in eukaryotic gene expression*, Nature 422, pp 633-637.
- [Brown 2023] Brown, Olen R., Hullender, David A., *Biological evolution requires an emergent, self-organizing principle*, Progr. in Biophysics and Mol. Biology, 182, 75-102.
- [Butterfield 2011] Butterfield, Jeremy: *Less is Different: Emergence and Reduction Reconciled,* Foundations of Physics: 41, 6, pp 1065-1135.

- [Carsetti 2020] Carsetti, Arturo, *Metabiology, Non-standard Models, General Semantics and Natural Evolution*, Springer.
- [Darwin 1859] Darwin, Charles, *On the Origin of Species*, Down, Bromley, Kent.
- [De Broglie 1947] De Broglie, Louis, *Au dela des Mouvantes Limites de la Science,* Revue de Métaphysique et de Morale, 52 (3/4) pp. 372-397.
- [Descartes 1642] René, *Traite de l'homme*, Oeuvres VI (Adam et Tannery), pp. 58-59
- [Driessen 2010 a] Driessen, Alfred and Nienhuis, Gerard (Eds.) *Evolutie: wetenschappelijk model of seculier geloof*, Kok, Kampen.
- [Driessen 2010b] Driessen, Alfred, *Evolutie bekeken met de bril van een natuurkundige*, in A. Driessen and G. Nienhuis (Eds), *Evolutie: wetenschappelijk model of seculier geloof*, Kok, Kampen, pp. 33-45.
- [Driessen 2015] Driessen, Alfred, *Life and Quantum Biology*, Acta Philosophica, 24 (1), pp 96-85.
- [Driessen 2016] *The Role of Philosophy as a Guide in Complex Scientific and Technological Processes*, PhilArchive, https://philpapers.org/archive/DRITRO-3.pdf.
- [Einstein 1935] Einstein, A., Podolsky, B., and Rosen, N., *Can quantum-mechanical description of physical reality be considered complete?,* Phys. Rev. 47, 777-780 (1935).
- [Feuerbach 1850] Feuerbach, Ludwig, *Die Naturwissenschaft und die Revolution*, Gesammelte Werke, Kleinere Schriften III, Bd 10, pp 347-368 https://www.ludwig-feuerbach.de/natur_rev.htm.
- [Hossenfelder 2020] Hossenfelder, Sabine, and Palmer, Tim, *Rethinking Superdeterminisme*, Frontiers in Physics, 8: 139, doi: 10.3389/fphy.2020.00139.
- [Jablonka 2014] Jablonka, Eva, and Lamb, Marion J. *Evolution in Four Dimensions, Genetic, Epigenetic, Behavioral, and Symbolic Variation in the History of Life,* Revised Edition, MIT Press, Cambridge, Massachusetts.
- [Johnson 2015] Johnson, Curtis, *Darwin's Dice, The Idea of Chance in the Thought of Charles Darwin*, Oxford University Press, Oxford.
- [Kim 2021] Kim, Youngchan et al. (21 authors), *Quantum Biology: An Update and Perspective*, Quantum Reports, 3, https://www.mdpi.com/2624-960X/3/1/6#.
- [Kirschner 2000] Kirschner, Marc, Gerhart, John, and Mitchison, Tim, *Molecular "Vitalism",* Cell, 100, pp 79-88.
- [Ma 2021] Ma, Liqiu, Kong, Fuquan, Sun, Kai, Wang, Ting, Guo Tao, *From Classical Radiation to Modern Radiation: Past, Present, and Future of Radiation Breeding*, Frot. Public Health 9, 968071, https://doi.org/10.3389/fpubh.2021.768071.
- [Mermin 1993] Mermin, N. David, *Hidden Variables and the Two Theorems of John Bell*, Rev. Mod. Phys. 65, 803, version 2018 https://arxiv.org/pdf/1802.10119.pdf.
- [Monod 1971] Monod, Jacques, *Chance and Necessity*, An Essay on the Natural Philosophy of Modern Biology, Knopf, New York.
- [Mulder 2023] Mulder, Valentin, Mermoud, Alain, Lenders, Vincent, and Tellenbach Bernhard, *Trends in Data Protection and Encryption Technologies*, Springer.
- [Muller 2017] Muller, Gerd B., *Why an extended evolutionary synthesis is necessary*, Interface Focus 7, 2017.0015, http://dx.doi.org/10.1098/rsfs.2017.0015.

- [Ramsey 2016] Ramsey, Grant and Pence, H. Charles, Introduction, in *Chance in Evolution*, Eds. Ramsey Grant, and Pence, H. Charles, The University of Chicago Press, Chicago.
- [Smith 1997] Smith, Maynard J. M., and Szathmary, Eors.: *The Major Transitions in Evolution*. Oxford University Press.
- [Snell-Rood 2021] Snell-Rood, Emilie C., and Ehlman, Sean M., *Ecology and Evolution of Plasticity*, in Pfennig, David W. (Ed.) *Phenotypic Plasticity & Evolution*, CRC Press, https://doi.org/10.1201/9780429343001.
- [Tang 2020] Tang, TC., An, B., Huang, Y. *et al.* Materials design by synthetic biology. *Nat Rev Mater* **6**, 332–350 (2021). https://doi.org/10.1038/s41578-020-00265-w.