

Emergence and Contingency in Modern Scientific Theories

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How to cite this paper: Kapodistrias, A., Katsiampoura, G., & Skordoulis, C. (2022). Emergence and Contingency in Modern Scientific Theories. *Advances in Historical Studies*, 11, 33-45.
<https://doi.org/10.4236/ahs.2022.112004>

Received: January 21, 2022

Accepted: April 26, 2022

Published: April 29, 2022

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Abstract

Starting from the second half of the twentieth century, there has been a rising interest, in modern scientific theories, about the notion of emergence. Its compatibility and explanatory power with theories that involve the study of complexity and nonlinear systems are expressed in many recent works in the field of philosophy of science. These works showcase an ongoing debate about emergence and reductionism, and despite the divergences of the definitions and the approaches regarding emergence, it is very often connected with the notions of non-predictability, complexity and contingency. Focusing on the later one, we will argue about the connection of emergence and contingency by focusing on three modern scientific theories that make strong cases for emergence. Starting with Chaos Theory in Mathematics, we have strong cases of the emergence of physical properties, as a result of non-infinite precision in calculating a system's initial conditions. In Evolutionary Biology, we have the theory of Punctuated Equilibrium and Stephen Gould's approach to the occurrence of species extinctions, and in History of Science, Cushing's theory for the role of Historical Contingency in theory selection in science, that showcase the connection between contingency and emergence. Based on this analysis, we propose the enrichment of the discussion concerning the Nature of Science (NoS) with the aspects of emergence and contingency embodied in modern scientific theories, highlighting their contribution to an educational environment that values the NoS.

Keywords

Emergence, Contingency, Historical Contingency, Punctuated Equilibrium, Non-linearity, Quantum Mechanics, Nature of Science

1. Introduction: A Review of Basic Terms and Concepts

Emergentism

Emergentism is a philosophy that occurred through scientific research in domains that mainly concern the study of complexity and utilize nonlinear dynamics (Bedau, 1997). Its central arguments evolve around the notion of emergence, according to which there are physical systems whose properties cannot be reduced to the sum of the properties of the parts from which those systems consist. We can summarize the main points of emergentist philosophy as follows:

1) Emergent phenomena are dependent on the underlying procedures that take place on the lower-level structures (base) from which they consist. They can only occur when such a lower-level structure exists and there are specific relations and procedures that have developed between their parts.

2) Simultaneously, emergent phenomena are independent of their base, in the sense that the base's properties don't suffice in order to predict and explain the novel properties that occur (Rigato, 2017).

The notion of emergence dates back to the mid 19th and early 20th century, when there was a vivid discussion about whether macroscopic phenomena such as biological life or consciousness can be solely derived from the physical sciences, or otherwise if it is possible for sciences such as biology or psychology to be reduced to the fundamental laws of physics. Those questions were first approached by the first British emergentists, whose main argument was ontologically materialistic (i.e. the physical world consists of matter) but also argued that matter forms structures on different levels, and at each level, radically novel properties occur with respect to the properties of the lower level. These approaches of emergence can be found in the works of J.S. Mill (1843/1930), Samuel Alexander (1920), C. L. Morgan (1923) and C.D. Broad (1925).

The above mentioned works do not really account for a common view on emergence, but they are characterized by some common elements that highlight a historical and philosophical background for emergentism. For example, it appears that the notion of emergence in these works is developed as an alternative to the view of the "Laplacian Demon" which is an ultimately deterministic and mechanistic view for physical procedures. Emergentists consider a level of matter organization, on which there exist mechanistic procedures, in the sense that the result of a sum of causes is the sum of their results, if every cause could act independently. On the other hand, they also view other levels of matter organization (chemical, biological), which do not account for such a superimposition of causes. As a matter of fact, J.S. Mill studied chemical replacement reactions and argued that the properties of the products of such reactions are not the sum of the reactant's properties.

The study of emergence in recent works shows that, especially since the mid 20th century, emergence has been established as a very powerful explanatory tool in theories that involve complexity and nonlinearity. Many philosophers of science

have developed their own definitions and approaches to emergentism and its applicability in physical theories. In order to give a clearer view about this discussion, we will present some generally accepted categories of emergence.

Strong Emergence: This is a category of emergence that argues that the impossibility of reducing a phenomenon or a property to the properties of its parts is not just an epistemological weakness, but also a result of a clear ontological distinction between the different levels of the organization of matter. This category is most common in biological systems or systems that generally consist of biological elements (i.e. global climate).

The main characteristic of a strongly emergent phenomenon is that of “causal novelty” which is the appearance of novel physical laws that not only cannot be reduced to lower-level laws, but they also supervene at them and define the behavior of more fundamental structures. This procedure is called “downward causation”, defined as: “Property P is an emergent property of a (mereologically-complex) object O if P supervenes on properties of the parts of O, P is not had by any of the object’s parts, P is distinct from any structural property of O, and P has a direct (‘downward’) determinative influence on the pattern of behavior involving O’s parts” (Bedau, 1997: p. 376).

Weak Emergence: This category of emergence is the most common among theories that involve complexity, complex systems, self-organization and non-linearity. At its core, we find the notion of non-predictability, which is the idea that a property is emergent when it is a systemic property that does not occur at any of its parts independently, but it appears in an unpredictable and unexpected way, regarding the laws we know about the fundamental level. Non predictability does not account for complete impossibility of reducing that property to a fundamental level, though, and this is why this kind of emergence is called “weak”, in contrast to strong emergence. Bedau (1997: p. 378) gives the following definition about weak emergence: “Macrostate P of S with microdynamic D is weakly emergent if P can be derived from D and S’s external conditions but only by simulation”.

Bedau’s examples for weak emergence include Conway’s “Game of Life” in mathematics, which is the time evolution model of a cell structure and Packard’s life evolution model that describes a population’s growth based on its capability to adapt to environmental changes (evolutionary memory). Robert Batterman (2011) studies emergent phenomena in Physics, and also approaches this category of emergence by arguing that the central point of emergence is not to argue about some downward causation, but to point out the explanatory limits of reductionist theories. In that sense, according to Batterman, a property is emergent when it occurs at breaking points at which our micro-level theories collapse and lose their explanatory power.

Contextual Emergence: According to Bishop and Atmanspacher (2006), descriptions of properties at lower levels provide necessary but not sufficient conditions for the description of higher-level properties. This means that these

“lower level” descriptions are not sufficient by themselves to logically produce the “higher level” descriptions. An immediate result is that the reduction of properties at a fundamental level is not possible, as in the case of the molecular structure as an emergent feature of a fundamental quantum mechanical description, or the example of temperature as an emergent property of a fundamental description based on statistical mechanics.

The “contextual emergence” approach is an epistemological tool that is useful for explaining the occurrence of radically novel properties, since [Bishop and Atmanspacher \(2006: p. 1773\)](#) suggest that for this explanation we must appeal to fundamental description in addition to “a strict definition of conditions that reflect specific possibilities in a given state”. Specifically, this means defining an equilibrium state that is based on a system’s macroscopic study (i.e. thermodynamic equilibrium). Then, this state is used as a reference state (which the micro-states approach asymptotically) and in that way, through a fundamental description and the definition of such a state, there can be a strict mathematical procedure to derive the higher-level properties. In their works, they use examples for this kind of emergence in Physics, but they also remark the possibility of extrapolating contextual emergence in sciences such as biology, psychology or the mind-body problem.

Contingency

Ian Hacking’s work “How inevitable are the results of successful Science?” is a study centered around the following question: “If the results R of a scientific investigation are correct, would any investigation of roughly the same subject matter, if successful, at least implicitly contain or imply the same results?” ([Hacking, 2000: p. S58](#)).

[Hacking \(2000\)](#) gives two different answers to that question, one realist and one constructionist. In this way, he connects the inevitability of successful scientific results with scientific realism, and claims that constructionists maintain a contingency thesis. This means that there can exist other, alternative sciences (i.e. physics evolving in a “non-quarkly” way) that study the same topic and provide equally successful results while being irreducibly different from our sciences and based on incompatible ontologies ([Boon, 2015](#)). The contingency thesis, therefore, gives a clear answer to Hacking’s question: the results of successful science are not inevitable.

At this point we have to point out that this definition and approach to the notion of contingency in science has been proposed aiming to answer the question about the inevitability of successful scientific results. Hacking’s contingency thesis is in fact compatible with some modern scientific theories, as we are going to demonstrate below. The theory of Historical Contingency in Theory Selection in Science by James Cushing, specifically argues in favor of the possibility of quantum mechanics evolving through a deterministic interpretation, instead of the Copenhagen interpretation. Moreover, the theory of Punctuated Equilibrium and Chaos Theory showcase a notion of contingency that is not only applicable to

Hacking's question about the inevitability of the results of alternative sciences, but showcase the possibility of scientific results being contingent within a certain theory, as a result of unpredictability due to increasing degrees of complexity.

2. Punctuated Equilibrium in Evolutionary Biology

Gould and Eldredge's Punctuated Equilibrium theory in evolutionary biology, is considered to be one of the most radical theories in the science of the 20th century. It was explained and analyzed in two articles in the journals *Models in Paleobiology* (1972) and *Paleobiology* (1977) and it is an antithesis to the long tradition in evolutionary biology, that of the Darwinian phyletic gradualism, which is based on the idea of a gradual and steady evolution of species across time. Punctuated equilibrium, on the other hand, is based on the idea that species evolution consists of brief periods of rapid changes, which are followed by long periods with minor or no changes (stasis). Gould and Eldredge's analysis, is centered on a non-linear and non-continuous species evolution, based on the mechanism of allopatric speciation, that is a key in remarking the limits of the Darwinian theory of natural selection for evolution.

Allopatric speciation is a mechanism of speciation according to which, a new species occur when a small, topically located population is geographically isolated from their maternal species. Then, this small population evolves into a new species due to strong isolating mechanisms that take place and prevent the gene flow between this species and its ancestors. This has a direct influence on the time of the occurrence of morphological differences between the species, since the morphological features that distinct the two species appear almost instantly after an event of geographical isolation, and it is only after that event that the mechanisms of natural selection take place in order to achieve equilibrium between the population and its environment. In the words of **Niles Eldredge and Stephen J. Gould (1972)**: "New species occur through the branching of a lineage, they develop rapidly inside a sub-population of the species and at first they appear in small region of the geographical range at which the ancestral species extends".

Another radical consequence of this theory had to do with the explanation of the "evolutionary trends" phenomena. In fact, the writers themselves claim that this was the most exciting part of their theory (**Gould & Eldredge, 1977**). Based on a conclusion by S. Wright cited in **Gould & Eldredge (1977)** who suggested that, as mutations appear stochastic regarding the selection mechanism in a population, we can see speciations as stochastic with reference to evolutionary trends, which are long term and commonly directed changes. Until then, the interpretation for evolutionary trends was merely an extrapolation of gradualism in larger scale evolution phenomena, with the mechanism of orthoselection being at its core.

With the new interpretation of punctuated equilibrium "we imagine multiple experimentations and infiltrations, on a stochastic basis, of geographically iso-

lated populations in new environments. There isn't something inherently directional in these infiltrations. A sub-total of these environments can lead to [...] new and improved efficiency. The improvement will be continuously bigger in this sub-total of local conditions. In this way, the overall result will be a grid of commonly directed changes, at which the first changes are stochastic" (Eldredge & Gould, 1972: p. 112).

3. Emergence and Contingency in Punctuated Equilibrium

In examining the relationship between emergence and contingency in the punctuated equilibrium theory, we will firstly focus on the relationship between theories of micro- and macroevolution, in order to analyze if species evolution, on a large time scale, occurs as an emergent phenomenon with respect to evolutionary procedures on smaller time scales. If this should be the case, we should be able to distinguish between evolutionary mechanisms and phenomena on different time scales. In fact, we can argue, through the study of recent works on punctuated equilibrium, that such a distinction is achievable.

Micro-evolution is the study of the evolution of a population in a relatively small time scale, in the magnitude of generations (Wosniack et al., 2017). On this level, we find gradual evolutionary procedures that are centered on genetic mutations, interactions between populations and their adaptability to a certain environment. These factors cause a certain level of diversity in a population's genome and they are arranged (Gontier, 2015) through the mechanisms of natural selection (fitness, competition). Generally, the main idea of micro-evolution is that, examining the passing of a generation within a population, we can approach the causal mechanisms of the changes observed through the phenomenon of genetic drift (the alteration in appearance frequencies of certain genes in a population's genome) and the mechanisms of natural selection.

Macro-evolution, on the other hand, refers to evolution in a larger taxonomical level than that of populations and examines phenomena that occur on large time scales, such as species extinctions, or the origins and divergence of evolutionary branches. At its core, we find the study of the mechanisms of speciation, based on empirical evidence provided from paleontological data (i.e. the fossil archive) and connect recent and older taxonomical groups.

The relationship between the mechanisms of micro and macroevolution is a central question and research topic to this day (Gontier, 2015; Huneman, 2017; Wosniack et al., 2017). Is it possible to preserve the laws and principles of microevolution as we shift from smaller to larger time scales, in order to approach phenomena on higher taxonomical groups such as speciation, extinctions, or the tempo of species evolution? The "mainstream" answer, that sets the tone in evolutionary biology for decades, would be the theory of Modern Synthesis. According to this theory, smaller and larger scale evolutionary phenomena can be approached through analysis at the micro level of genetics. As Gontier (2015) shows, notions such as adaptability and natural selection were considered as

procedures at the genetic level and were confused with genetic fitness or selection. We could say, therefore, that in the classical paradigm of evolutionary biology, there is a remarkably reductionist culture that aims to reduce larger scale phenomena to laws and procedures of smaller scales, in the name of the search for a “generalized continuity and stability that the founders (of Modern Synthesis) and Darwin regarded as very important for the functionality of natural selection” (Gontier, 2015: p. 232).

The reductionist approach in evolutionary biology is closely related to Darwinism and the framework of phyletic gradualism as an extrapolation of the results of natural selection on the evolutionary history of species, as described above. Therefore, any objections and alternative theories concerning the shift of time scales in evolution, begins with the challenge on this framework, which was posed in Gould’s and Eldredge’s work about punctuated equilibrium. They set the foundations of evolutionary biology as a theory for macroevolution, based on their interpretation of evolutionary trends. It seems that they don’t view their theory as a complete departure from Darwinism, but as “the same procedure that functions in a different way at different levels of complexity and organization” (Gould & Eldredge, 1977: p. 139) arguing that it can function as a model for species selection that is based on the punctuated equilibrium image and the fact that speciations are of stochastic nature regarding evolutionary trends. Instead of viewing macroevolution as an extrapolation of the same mechanisms from the level of populations and generations to the level of larger time scales and higher taxonomical groups, we can focus on the stochastic nature of speciations and in this way distinguishing between microevolution and macroevolution (Gould & Eldredge, 1977).

Similar conclusions can be drawn from other issues of time scale shift that don’t necessarily involve punctuated equilibrium (Gould, 1990). Gould, in his book *Wonderful Life*, focuses on the issue of massive evolutionary changes, such as extinctions, and argues about the role of contingency in the evolutionary procedure. According to Gould, massive extinctions are the result of large ecological disasters caused by planetary or astronomical causes, and therefore a species survival or extinction appears as contingent to evolutionary biologists. In recent works, there have been efforts of modeling of such a contingency, which are characterized by complex dynamic systems that picture a species’ course towards extinction. Huneman (2017) mentions patterns of partial and total contingency and argues that in models of total contingency, an extinction is more probable at each time step due to larger divergence from a species’ adaptive optimal state at a given environment and moment in time. Finally, he concludes that macroevolution appears as contingent with respect to the dynamic systems of selection that describe microevolution. This is, therefore, a point that we can argue about a close relationship between emergence and contingency, as the stochastic procedures at the level of macroevolution that not only cannot be reduced to procedures of microevolution, but they supervene at them and define the framework within which they shall function.

4. The Case of Chaos Theory

Starting at the second half of the 20th century, with Lorenz's equations for the atmosphere, chaos theory has been vastly used in various scientific disciplines such as population biology, fluid mechanics and thermodynamics etc. while in the last decades the theory has been introduced in the study of economic models. Why is the study of non-linear and chaotic systems so special?

The difficulty at solving them analytically gave birth to different mathematical approaches and became an epistemological turning point with past epistemologies. The main characteristic of linear systems is that they can be divided into separate parts, which can be solved separately and give us a definitive result about a system's evolution. This simplification of complex systems, along with its methods (Laplace transformations, Fourier analysis), is not compatible with the study of non-linear systems, which are used in many models for describing physical (and not only) phenomena. The qualitative, holistic study of non-linear dynamic systems, the geometrical way of approach, self-organization and non-predictability are not only novelties that the study of chaotic systems brought to the surface, but they are also the reason that for many philosophers of science, this study is a sound example for the limitations of reductionist approaches and the necessity for emergentism. In the next part we will describe exactly how emergentism and contingency are inherent in the study of non-linear and chaotic systems.

Initial Conditions and Non-Infinite Precision

Chaotic systems are deterministic. This means that they are described by differential equations, which do not leave any space for probabilistic interpretations to a system's evolution. A crucial part of the geometric way of solving these systems is at first the determination of their attractors, which are regions on the phase diagram that "attract" a set of neighboring trajectories. Then, we determine exactly what kind of equilibrium (i.e. stable node, unstable node) each attractor represents. In chaotic systems, these regions are called strange attractors and the system approaches these regions non-periodically, following a trajectory that never passes from the same state twice. Such is the movement of the double pendulum, for instance. In time continuous problems, the attractor kind depends on the complexity degree of the system (or its dimensions), so that in one dimensional problem our attractors are points, in two dimensions we have limit circles and in three (and more) dimensional problems we have the strange attractors.

A key feature of chaotic systems is their sensitivity to their initial conditions. In non-chaotic systems, two separate, neighboring sets of initial conditions, that belong at to the same "basin of attraction" of the phase space, will eventually end up to the same final state, according to the evolution dictated by the system's attractor. Chaotic systems, on the other hand, two separate trajectories of the system's phase diagram that begin from close initial states, will eventually diverge

very quickly from each other and will evolve very differently. This has a very significant consequence, as it becomes impossible to predict a system's future state, if we don't know its initial conditions with infinite precision. It has been proven that these trajectories diverge from each other exponentially, according to the Lyapunov factor, and that for every chaotic system, with however small error at the initial condition's measurement, there is a time limit beyond which, our predictive capabilities fall apart. Thus, since our computational techniques don't allow for infinite precision (zero error) at the measurement of initial conditions, non-predictability becomes a foundational characteristic of any chaotic system and the final outcome of a system's evolution appears highly contingent.

We can encounter several foundational arguments for emergence and emergent properties in chaotic systems, based exactly on their sensitivity on initial conditions. Emergent phenomena may occur due to a certain weakness of our scientific tools to predict the occurrence of a system's novel properties and behavior. Newman (1996) specifically, is based on C.D. Broad's definition for emergence that states that every prediction of the occurrence of novel properties is impossible, even if we have an ideal theory for a system's dynamics. By this definition, he highlights that non predictability of novel properties accounts for epistemologically emergent phenomena, since it is based on such restrictions (Newman, 1996: p. 256): "chaotic systems prevent a definitive prediction in two ways that Broad could have been referring to in his notion of inability of predicting the occurrence of emergent properties. First, the sensitivity to initial conditions excludes the prediction of a property's occurrence even if we have every information about the system that we are studying. Second, this sensitivity and the restriction in measurement precision, prevent us from obtaining every information for the system in study. This means that predicting the occurrence of certain properties of a chaotic system is impossible".

In a similar way, Silberstein and McGeever (1999) point out that chaos theory highlights the problems of reductionism, since that, despite the deterministic dynamics of chaotic systems (differential equations), there is no predictive capability, because of the restriction in the precision of a measurement. For these reasons, chaotic systems showcase epistemologically emergent behaviors.

5. Historical Contingency in Theory Selection in Science

The next theory that makes a case for emergence and contingency is Cushing's theory for historical contingency in theory selection in science (Cushing, 1990, 1992, 1994, 2003). Cushing's argumentation about historical contingency is based on the historical example of the quantum mechanics interpretation "race". The theoretical framework on which his theory is founded, is that of theory underdetermination in scientific practice. This is Duhem and Quine's argument, in the former's work titled *The Aim and Structure of Physical Theory* (Duhem, 1982). The issue of underdetermination of scientific theories occurs during the search for acceptance criteria for a scientific theory. Thus, the problem of underdeter-

mination can be summarized in the following contradiction, that Cushing (2003) calls “the problem of a scientific realist”: “Should there exist two empirically sufficient and successful scientific theories, that agree upon every empirical test and therefore are observationally equivalent and are supported by radically incompatible ontologies, then this situation can prevent a scientific realist’s research for one correct scientific theory that provides a real world image”. Cushing doesn’t argue that underdetermination takes place in every case of theory selection, but there have been specific cases that it has been encountered. The case of the history of quantum mechanics is such a case since in a reductionist approach, underdetermination can influence theory selection. There occurs a crucial task, therefore, for scientists to determine the foundation of non-evidential criteria and the role of historically contingent factors that affect a theory selection (Cushing, 2003).

In his works, Cushing specifically studies the conflict between the two main interpretations of quantum mechanics and highlights that the mathematical formalism of quantum mechanics is empirically adequate and can be supported by two ontologically incompatible interpretations: Copenhagen’s School non deterministic interpretation, and Bohm’s non local but deterministic theory of hidden variables. By studying this procedure, he concludes that the prevalence of one theory over the other was a historically contingent process that is not solely grounded on logically assessing the two theories but other, historically contingent factors, also played a significant role in the outcome. Thus, what is considered successful and commonly accepted by the scientific community is “*a contingent and not unique product*” (Cushing, 2003: p. 455).

Emergence and Historical Contingency

Cushing’s conclusion, therefore, while studying the special case of quantum mechanics is that we should search for the base of non-evidential criteria and the role of historically contingent factors that led to the selection of one theory over the other. Cushing analyzes these factors excessively and argues that the most important were the general tendency of that era’s scientific community to consider matters of formalism more urgent than those of ontological interpretations and a series of other factors that include the psychology and relationships between the Copenhagen group and professional and sociological factors that made the Copenhagen hegemony more necessary and demanding (Cushing, 2003).

Since we have two mathematically equivalent and empirically adequate theories, and there aren’t other logical, objective criteria, like a theory’s capability of problem solving or its fertility (its capability of suggesting new paths for research), Cushing concludes that the dominant interpretation of the theory was in fact *selected*, based on historically contingent criteria.

How does Cushing’s mechanism for theory selection in science correspond with the notion of emergence? Cushing argues that for theory selection, empirical data aren’t sufficient, or other criteria for preference such as the simplicity or

consistency of a theory. Nature poses a problem's "boundary conditions", provides empirical data that pose strict restrictions, leaving a small margin for selection. From there, theory construction (Cushing, 2003: p. 465): "is a rich process, during which a lot of factors intervene and partially overlap [...] How things could have turned out very differently at certain critical situations, and why this didn't happen, can prove to be equally important with the reasons for which science has made the rational choices".

Cushing provides a complex, interdisciplinary study of the subject of theory selection, through the prism of "interior" and "exterior" factors, in order to highlight his suggested mechanism: at the critical point where one formalism can be supported by different ontologies that are empirically adequate, we have the intervention of historically contingent factors, different causal chains are formed, and a selection is made. A different chain of events could have led to a different selection. Thus, we observe that a new scientific theory, with radically new properties (like uncertainty and non-locality in the two cases of quantum mechanics) *emerges* through this complex process that can occur only if we study the logical criteria along with historically contingent factors.

6. Epilogue: New Insights in the Nature of Science (NoS)

During the past few decades it has been widely acknowledged, by researchers in science education (Stefanidou et al., 2013, 2017), that Nature of Science (NoS) is a key concept in science teaching, crucial for the students' scientific literacy. This means that, alongside fundamental scientific theories, laws and models, education must be able to give insight to scientific knowledge itself; how science is produced, its subjectivity to change (tentativeness), its historicity, the relationship between objectivity and subjectivity in science, based on the consensus of the seven features of NoS. At this point, we would like to address some of the above showcased aspects of emergence and contingency in modern scientific theories, regarding the contribution that they could provide in an educational environment that values the NoS.

We believe that today's secondary science curricula mostly reflect the reductionist tradition and the mechanistic approach to physical theories. Secondary school students in science courses are solely taught about linear systems, analytical solutions and simple models across all science courses (from Newtonian Mechanics or Atomic Physics to Mendelian Inheritance in Biology) that generally leave the students with a reductionist conception about how science functions, and the concept of emergence, even in subjects that could be introduced (i.e. Chemistry), is absent. This could potentially create a problem regarding the notions of NoS that students obtain in secondary education and we believe that through simple examples of modern scientific theories like the ones we discussed above, these notions could be more fairly grounded. The study of emergence, contingency and their relationship through these theories could be useful in many ways. Punctuated Equilibrium and Historical Contingency can address

many aspects of the NoS (tentativeness, validation of knowledge, hypotheses, laws, theories and models) whereas simple nonlinear systems and their applications can open paths to modern interdisciplinary approaches and the study of “real world” science. A discussion about contingency and the inevitability of the results of science, in general, could also provide insight in scientific theories as not closed self-contained systems but contingent in nature, allowing the emergence of new qualities in the course of the description of natural phenomena. In this way, a modern Science Curriculum that emphasizes on NoS concepts could highlight a new image of science as being not mechanistic in nature but having an open character underlying the possibility of multiple solutions to real-life problems.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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