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REVIEW ARTICLE

Contingency versus inevitability: a review and reinterpretation of Stephen Jay Gould's book "Wonderful Life—The Burgess Shale and the Nature of History"

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ABSTRACT

In 1989, Stephen Jay Gould published his Wonderful Life: "High in the Canadian Rockies is a small limestone quarry formed 530 million years ago called the Burgess Shale. It holds the remains of an ancient sea where dozens of strange creatures lived a forgotten corner of evolution preserved in awesome detail. In this book Stephen Jay Gould explores what the Burgess Shale tells us about evolution and the nature of history". Gould, based upon a reinterpretation of the famous fossils from the Burgess Shale, proposed a conclusion that was revolutionary at the time, because it was centred on the notion of contingency in the course of biological evolution. The very last paragraph displayed in particular the following sentences: "This response does not cite a single law of nature; it embodies no statement about predictable evolutionary pathways, no calculation of probabilities based on general rules of anatomy or ecology. I do not think that any 'higher' answer can be given, and I cannot imagine that any resolution could be more fascinating." In this essay, I intend to criticise Gould's conclusions and to provide a new reinterpretation of the history of life, based not on contingency but on the inevitability of evolution.

Keywords: biological evolution; traditionalism; Darwinism; contingency; tape of life; laws of nature; evolutionary inevitabilities

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1. Introduction

1.1. The evolutionary sciences at the end of the 20th century

During the second half of the 20th century, the evolutionary sciences were mainly represented by the *Modern Synthesis*, including data from natural history, systematics, palaeontology, zoology, and botany. The Synthesis reunited neo-Darwinism (which envisions evolution by natural selection without referring to any kind of Lamarckian mechanism), Mendelism (The three Mendelian laws are: i) association: gamete purity or trait uniformity of first generation hybrids; ii) dominance or segregation of alleles; iii) independence of character assortment) and population genetics. To sum up, the Synthetic theory states that, because of random mutations and random recombination events, populations are genetically variable. Through changes of gene frequencies occurring by genetic drift, genetic flow, and more specifically natural selection, those populations evolve. Most of the adaptive genetic variations produce only weak phenotypic effects, resulting in gradual phenotypic changes (although some alleles with weak effects may be advantageous). Speciation leads to diversification and normally to a gradual reproductive isolation between populations. Viewed over sufficiently long periods of time, all these processes can result in such changes that new major taxonomic groups can be defined (genera, families, and the like).

In spite of his criticising Darwinism and the Modern Synthesis, Gould's view of evolution remains relatively orthodox and ultimately Darwinian. This point will be of special significance in the present argument. More specifically, Gould champions a conception of evolution relying mainly on chance: contingency.

In philosophy, contingency refers to the eventuality, the possibility, the probability that something might or might not exist or be different or happen or not happen, without any necessity. According to French philosopher Alfred Fouillée, "Contingency involves relying on an indeterminate cause, explaining no more an effect than another, thus providing no determinate solution to the problem at hand". In other words, contingency means the existence of a reality that may not exist.

Two things are implied if an occurrence is said to be contingent: i) this event might have not taken place; ii) nothing implies that this event was necessarily meant to be. Contingency is then closely related to uncertainty, as opposed to necessity, which would not have any justification. Thus, what is contingent would be fortuitous, accidental, occasional, uncertain, hence dependent on chance, or even insignificant (at least, a priori). As Leibniz would say, the contingency of an occurrence means that its opposite could have happened. In this way, Gould very simply defines contingency as the unpredictability of evolution (see pp. 283–291[1]).

There is however something more about contingency: path-dependency, the fact that a given event might dramatically influence subsequent occurrences. In this way, Gould champions the idea that "*with just a few small and judicious changes*"[1] the South might have won the American Civil War. In a similar way, Thierry Lodé points out that "*each event increases the probability of the following episode. Contingency is all about the loose horseshoe that will cause the horse to fall, hence the fall of the rider who will not be able to deliver his message to the general, who will lose the battle. At each step, a very tiny occurrence produces an effect that another event will enhance further. All those many tenuous and insignificant changes accumulate more and more in the history of life*"[2]. Therefore, if a particular occurrence does not take place in another fictitious narrative, then the subsequent history will necessarily be partly or totally different from the real narrative as it actually took place.

1.2. A comprehensive abstract of the book

More than 500 million years ago, strange creatures inhabited seas and oceans around the globe: "Opabinia*, with its five eyes and frontal 'nozzle';* Anomalocaris*, the largest animal of its time, a fearsome predator with a circular jaw;* Hallucigenia*, with an anatomy to match its name*"[1] and many others. The Burgess Shale contains many fossils from this extraordinary fauna, whose richness took almost a century to discover comprehensively, leading to a profound reappraisal of traditional representations of the history of life. Here Stephen Jay Gould tells us about the history of this scientific revolution, presented like a criminal investigation. From now on, we must understand evolutionary facts as both perfectly logical and explainable *a posteriori*, yet utterly unpredictable and, what is more, not reproducible. Contingency, the key word in the history of life and the history of man, is the very essence of the living. As in Frank Capra's film, '*It's a wonderful life*' because it is so unique and unpredictable.

1.3. The setting of the Burgess Shale and the work of Charles Doolittle Walcott

At the beginning of the Cambrian era, more than half a billion years ago, a wide variety of marine invertebrates appeared in a very short period of time on the geological scale. Many of these animals were killed in a single, brutal accident (such as a '*local mudslide*'[1]) and their bodies exposed to exceptional physical and chemical conditions for fossilisation. As a result, even their soft parts have been fossilised (usually, only hard parts can be fossilised, such as cuticles, carapaces, shells, endoskeletons, tree barks, leaf veins, etc.).

The Burgess Shale is now part of the Yoho National Park in British Columbia, Canada. This is where the American palaeontologist and geologist Charles Doolittle Walcott discovered in 1909 huge quantities of fossils from the Cambrian period (570 million years ago). Every year until 1917, Walcott took the time to excavate these highly diverse and well-preserved fossils. Altogether, he unearthed about 80,000 fossils belonging to an entire extinct ecosystem. They were exclusively small invertebrates (a few centimetres at most) whose particular shapes and anatomies are still nowadays a source of wonder.

Some of these small marine animals displayed extraordinary features, such as the five eyes of *Opabinia*, or the bulbous head of *Hallucigenia* (which may not even be the front part of the body) and its seven pairs of sharply pointed spines, its tubular tail (although it is not known whether it is the rear end of the body), the seven tentacles along its back, and the six small tentacles (perhaps three pairs) at the base of its tail. However, in order to classify them, Walcott merely viewed them as ancestors of today's marine fauna. For instance, he considered *Hallucigenia* as nothing but a 'worm' (a very vague term that has no evolutionary significance in modern phylogenetic classification).

As a professionally very busy man, Walcott never had the opportunity to study his own discovery thoroughly. After his death in 1927, these fossils did not receive the attention they deserved for almost half a century.

1.4. Reconstruction of the Burgess Shale

Gould then presents the work of three more recent palaeontologists, Harry Whittington, Simon Conway Morris, and Derek Briggs[1]. In a '*five-act drama*' from 1971 to 1985, they carried out a new, comprehensive and original survey of the Burgess Shale. Walcott indeed seems to have either misinterpreted the fossils or simply put them away in a drawer and forgotten about them. And yet, they provide by far the most important evidence ever of the anatomical diversity of animals throughout the history of living organisms. These fossils are so extraordinary and diverse that they have long been the subject of controversy.

For example, in 1971, Whittington questioned the idea of *Marrella* belonging to the Trilobite clade (Walcott's original interpretation) by publishing a monograph describing it as a unique and atypical animal belonging to no modern group. Together with Conway Morris and Briggs, they concluded that most of the Burgess specimens (between 80% and 90%) were unique Arthropods belonging to new phyla. In this light, the Cambrian period came to be considered as the richest in animal disparity ever documented.

Here Gould introduces the subtle difference between diversity and disparity. Diversity refers to the number of different species, while disparity is based on the set of organisation plans (*bauplans*). During the Cambrian era, it appears that disparity was maximal whereas diversity was apparently limited. Then, in the later stages of the history of life, the trend turned completely around.

Thus, during this period, nature seems to have been testing a wide variety of organisation plans, most of which failed and disappeared without leaving any offspring because they were wiped out in an event in which not only natural selection seemed to be abolished but, as Gould suggests, seemingly random factors also operated. In fact, it is considered that chance decides which forms disappear and which survive when most living species are eliminated during a major biological crisis. In other words, in the Cambrian, an observer could never have known *a priori* which species would be eradicated from the Earth's surface without descendants, and which would remain. For example, it is because their distant two-eyed ancestor survived that today's animals have two eyes. But if the five-eyed *Opabinia* had survived, today's fauna would be made up of five-eyed animals, because it is not possible to know whether having two eyes is a better evolutionary advantage than having five. We shall see that this involvement of chance is debatable.

A favourite method of Gould's is to tackle received ideas which, in his view, derive from prejudices based on anthropocentric thinking. In particular, he wondered how Walcott could have made such gross misclassifications of the Burgess animals. According to Gould, Walcott was under the influence of traditional representations and, with the help of a mental 'shoehorn', could only 'force' these animals into the classification then used. An image as striking as a mental shoehorn can be that of a clumsy child trying to fit a cylinder into a square hole. In this view, Gould considers that the reconstruction of the Burgess Shale "[…] *documents […] this great revision in our concepts about early life […] in the general context of an evolutionary theory partly challenged and revised by the story itself*"[1]. Gould indeed insists on two common errors in the traditional interpretation of evolution:

1) The "*classic 'textbook cases' of 'evolution'*", which show evolutionary lineages as progressions, such as "*the march of progress"* illustrated by a series of hominids gradually straightening out towards the final 'modern' man (see pictures pp. 30-35[1]);
2) The representation of the evolutionary tree as a '*cone of increasing diversity*'[1], "[…] *in a conventional manner chosen to validate our hopes for predictable progress*"[1]. As a matter of fact, the tree should be presented as a branching bush with many disrupted branches standing for evolutionary dead ends, highlighting 'explosive' diversification during evolutionary radiations and drastic decimations during major biological crises.

In his argument, Gould shows how our representations and prejudices prevent us from taking a different path and considering alternative approaches to a new response that challenges traditional views. These preconceptions seem to be of significant importance because they reveal a certain vision of the world and of man's place in it that is completely inverted in relation to classical and conventional conceptions.

The reconstruction of the Burgess Shale has had a huge impact on our understanding of the very nature of the history of life on Earth. Indeed, *Opabinia*, *Wiwaxia*, *Anomalocaris*, and *Hallucigenia*, the unlikely creatures with striking and bizarre anatomies presented in the book's many illustrations, reveal a simple thing about the history of life: contingency. We are, but we might as well never have been, and we owe our presence and our life (our survival) only to sheer luck. Among the many long-extinct organisms, consider *Pikaia*, living near the ancestors of today's Arthropods, the oldest known Chordate and, in a way, our distant ancestor. Hence a central idea in Gouldian evolutionary thought: "*Wind the tape of life back to Burgess times, and let it play again. If* Pikaia *does not survive in the replay, we are wiped out of future history — all of us, from shark to robin to orangutan. […] And so, if you wish to ask the question of the ages–why do humans exist?— A major part of the answer [...] must be: Because* Pikaia *survived the Burgess decimation*" [1]. Wouldn't such a vision make your head spin? Looking down on our 545-million-year-old world, we are faced with a grand and fascinating, but also frustrating and agonising vision of our fragility.

2. A constructive critique

Stephen Jay Gould has exceptional insight and open-mindedness. In all his works his writing style is striking. The importance of Gould's contribution to the advancement of evolutionary science is beyond question. Even today, many of his writings remain extremely relevant.

Despite some of the book's minor flaws (too long, unbalanced, and sometimes too detailed), Gould's merits eventually come to a surprising end. Like many other scientists denouncing professions of faith, Gould finally falls into the very traps he claims to avoid. The reconstruction of the Burgess Shale can ultimately be considered from a completely different, equally scientific perspective. As an alternative to Gould's predominantly contingency-based story, I propose another that appeals to evolutionary inevitability. The final consequences could then be radically different.

2.1. A step-by-step critique

2.1.1. Some uncertainties

The following two uncertainties can be raised about the Burgess Shale fossils:

Cambrian disparity may be exaggerated and apparently divergent evolutionary groups may ultimately be phylogenetically related; the whole phylogenetic analysis may, in a more general way, be flawed[3];

In this first period of animals with hard parts, the number of fossils could have suddenly increased, leading to the illusion of a great evolutionary radiation as a result of a possible sampling error.

2.1.2. Minor causes, major effects

As previously stated, in his definition of contingency, Thierry Lodé introduces the idea that probabilities increase continuously in the course of evolution, as each occurrence will enhance the probability of the next (in contrast to dice casting where probabilities remain constant). The following two comments are required:

1) First of all, Lodé seems to be embroiled in a form of circularity between contingency and probability: does contingency cause an increase in probability, or does the increase in probability cause contingency?
2) Secondly, it seems to me that even if such a hypothesis involving a probability increase at each contingent step does exist, it cannot be generalised, far from it. Indeed, many 'small chance' events will remain totally inconsequential (e.g. the rider realising the horseshoe is loose only after arrival). Our daily lives, filled with totally insignificant and mostly impactless events (although these aspects are obviously partly subjective), reveal such an idea. It is quite possible for a benign event to have equally benign consequences, such as a loose horseshoe that will only slightly slow the horse down. In the end, it seems that most of these 'small chance' events will be nothing more than insignificant occurrences drowned out by countless other insignificant occurrences. Therefore, it seems to me unjustified to try and devise a theory of contingency from such circumstances.

2.1.3. Chance, unpredictability, and contingency

On several occasions, Gould states that "*[mass extinctions] may result from environmental change at such a rate, and with so drastic a result, that organisms cannot adjust by the usual forces of natural selection*"[1]. He then points out that "*[w]e have some indications that true randomness may play a role*"[1], and that "[…] *we must entertain the idea that some groups lose by something akin to sheer bad luck*"[1], meaning that "[…] *mass extinctions preserve or annihilate species at random*"[1]. In other words, decimations are random, as all living organisms have the same probability of surviving or not surviving, so they can be said to be "equiprobable". Gould then asks: "[…] *how could we possibly know […] which groups were destined for success?*"[1] "[…] *how can we know [...] what the next episode of mass extinction […] will require?*"[1] He answers that "*[u]npredictability must rule […]*"[1]. As a result, because "*[…] any pathway proceeds through thousands of improbable stages*"[1], "[…] *eventual results [of evolution] cannot be predicted at the outset*"[1]. This is the very definition of contingency.

2.1.4. Random decimations

The fact that the rules of natural selection are abolished during mass extinction events does not imply that the organisms concerned have an equal chance of survival. In this case, all organisms should be anatomically, physiologically and evolutionarily perfectly equivalent. This simply does not make sense. Organisms of the same or different species are necessarily unequal (without any value judgment). This fact underpins polymorphism and biodiversity. Considering all organisms as equiprobable seems idealistic, simplistic, and unscientific.

First of all, the survival of an organism cannot be compared to flipping a coin or rolling a dice, as all outcomes are theoretically equiprobable. The probability of getting "tails" is 0.5, the same as the probability of getting "heads", and the probability of getting a 6 is about 0.167, the same as getting any other side of the die. Such draws are very simple events, as opposed to the tremendous complexity of living organisms. The survival of an organism involves a number of parameters that are impossible to quantify. In this view, two different organisms cannot be conceived of as having equal probabilities of survival (the probability that they have the same probability of survival appears to me as vanishingly small).

Gould argues that no advantage in terms of functional efficiency was detected by comparing the anatomy of the Burgess organisms, insisting that "[...] *we have no idea what such an advantage might be*"[1]. I am not an expert in palaeontology, but just from fossils, making such comparisons seems to me rather difficult, if not impossible. Indeed, even the comparison of living organisms (which obviously nobody wants to do) would be extremely difficult, not least because such studies would be criticised as being subjective and anthropocentric. How is it possible to answer questions such as: what makes one organism more 'efficient' than another? On the basis of what criteria? Under what conditions? Furthermore, the fact that no differences are identified does not mean that the organisms are actually equivalent. As extreme conditions prevail during major biological crises, even the tiniest, and therefore inconspicuous, differences could play a decisive role. Moreover, in no way should the absence of an identified evolutionary advantage mean that there is no such advantage.

Such an authoritative and naive conclusion somehow distorts reality. It seems hardly possible to ever get a clear picture of what really happened over half a billion years ago, down to the very last detail. It seems to me beyond any reasonable doubt that such an advantage, however small, did exist, more probably than a perfect equality of chances anyway. As a matter of fact, this alleged equality of chances during decimation sounds more like a profession of faith than a scientific "truth". Because it is part of a "Darwinian" conception of life, as if "every being had the same chance", such a statement seems merely gratuitous and comforting. It can even be seen as the result of a biased and tautological reasoning, as imposing equal chances from the start can only lead to contingency (just as the regularity of mutations automatically leads to the molecular clock). The same logic entails chance as coming from "two causally independent sources".

It seems to me more probable, reasonable, and realistic to consider that the organisms were unequal, even slightly so, in such a decimation. From this perspective, a decimation may be unpredictable but, as we shall see, certainly not random. And finally, as Sterelny and Griffiths state, "[…] *chance extinction, strictly interpreted, does not make sense of the claim that the patterns of failure and success are retrospectively intelligible*"[4].

2.1.5. Confusing "unpredictability" and "randomness"

Gould's interpretation reveals another problem: the typical and common confusion between an unpredictable event and a random event. However, the two concepts do not appear to be equivalent.

1) An unpredictable event may not be random: the date of our death is unpredictable, even in the very short term; nevertheless, death, being absolutely certain, is not at all random;
2) An *a priori* random event may not be unpredictable, such as a weather event (like a cold snap), or a geological event (like a volcanic eruption), because meteorologists and geologists are precisely supposed to best predict these events;
3) Furthermore, seemingly random and unpredictable events are not so, as is the case with solar and lunar eclipses. As Hubert Reeves said, it is now possible, thanks to the laws of celestial mechanics, to predict with great accuracy the eclipses that will occur thousands of years from now. It is also possible to verify the astonishing accuracy of records based on astronomical observations made a few thousand years ago in ancient China[5].

Therefore, it seems unreasonable to claim that a random decimation will lead to an unpredictable outcome. It is one thing for the results of a decimation to be unpredictable; it is quite another to insist that they are random. I think that these results are not random, because the affected organisms showed differences, however tiny, as has already been mentioned. This is a plain and simple statement, not a value judgement. No organism is supposed to be superior to another. However, as surviving a large-scale ecological disaster is a matter of anatomical, physiological or other characteristics, the chances of survival cannot be the same for everyone. Such a coincidence seems so unlikely that even considering it sounds ridiculous.

2.1.6. The relativity of unpredictability

To say that an event is unpredictable is necessarily an *a posteriori* statement, not an *a priori* one, since by definition what is unpredictable cannot be predicted. Moreover, it is for us humans, with our inherently limited intelligence, science, and technology, that an event is unpredictable. Forecasters are able to predict most weather events, but some very isolated events, such as tornadoes and hailstorms, elude prediction, sometimes with devastating consequences. Does this mean that these events were absolutely and truly unpredictable? Were our hardware more powerful, our software better designed, our weather stations more numerous, what would our forecasting capabilities be? I think they would make us capable of predicting such isolated events, despite what chaos theorists and the famous "butterfly effect" would have to say. Thus, to claim that the outcome of a decimation is unpredictable, as Gould does, forces me to ask: unpredictable for whom?[5]

2.1.7. The limits of the notion of contingency

To me, the very notion of contingency presents some limits which have apparently never been clearly defined:

1) From a scientific point of view, it seems less parsimonious to invoke a number of isolated and independent events that have had a punctual influence on the evolutionary process than to assume that some general mechanisms have constrained evolution in a privileged direction;
2) Moreover, as stated by Douglas Erwin (comparing contingency and convergence–see below), whereas it has been widely shown that "[…] *convergence is ubiquitous at many different taxonomic levels*", "[…] *contingency is much harder to test for*"[6];
3) Furthermore, "[…] *if contingency is as ubiquitous as Gould claimed, then adaptive selection may play less of a role in evolution, at least over longer time scales, than many evolutionists would accept*"[6], which stands opposed to Darwinian evolution. Sterelny et Griffiths concur as they state that "[…] *the contingency hypothesis about adaptive complexes is inconsistent with [the] adaptationist conjecture*"[4].

2.1.8. Uniqueness, non-reproducibility, and contingency vs. convergence

Gould considers that contingency is proven by unique and non-reproducible events. An event that occurs only once and, moreover, cannot be envisaged repeatable throughout the history of life, means that the path taken is an unpredictable choice among an infinite number of others.

Yet how certain is the uniqueness of certain events? How certain their non-reproducibility? Convergence[7,8] can be seen as specifically involving repeated evolutionary events. Conway Morris precisely asserts that "[…] *everywhere you look evolution is hedged in by convergence*"[8]. In such a view, the repetition of evolutionary occurrences seems to be the rule more than the exception.

In my opinion, an event can be explained as unique because it is inevitable in a given place at a given time. Each event needs to be seen as part of a huge network of events, not just a chain of events, all of them directly or indirectly interconnected by cause-and-effect relationships. In this perspective, the occurrence of each event is due to a set of concurring causes both in space and in time, which sooner or later will make this event unavoidable, inescapable, inevitable. Such reasoning is not based on any probability but on absolute certainty. Hence no contingency.

A common example is the giant meteorite (at least 10 km in diameter, possibly much larger) that fell to Earth 66 million years ago and caused the extinction of the "dinosaurs" (in the familiar sense of that word). According to the standard scientific view, this event represents a typical case of contingency, because if the meteorite had not fallen to Earth, dinosaurs might not have disappeared, mammals might not have undergone any evolutionary radiation and primates might not have appeared, let alone our species. It would be as if the meteorite had literally come out of the blue, without any clear cause, which is obviously totally wrong. The reason why the meteorite fell to Earth is that it was orbiting the Sun, under specific physical forces (mainly the gravitational force). This particular orbit can be explained by previous events, such as the meteorite being possibly located inside the asteroid belt (between Mars and Jupiter), from where it would have been ejected by colliding with another meteorite. In short, a whole series of cause-and-effect relationships needs to be taken into account, in which all events are linked, which in a way makes the fall of the meteorite inevitable and not contingent. Predictable? Maybe not. Random? Certainly not. In such a perspective, the meteorite could not but fall on our planet. Not because it was intended, not because it was written somewhere, but because it was inevitable. The consequences of the fall can also be dealt with by the same type of reasoning, starting from what the world, in particular the living world, was like at the precise moment the meteorite fell.

Such an inevitable event may well be unique and non-repeatable. So, Gould's conclusion is not the only one possible in absolute terms. Yet this is the only acceptable conclusion if one considers that the world is driven by chance–all in all, a Darwinian world.

2.1.9. Convergence and evolutionary inevitabilities

Conway Morris insists that "[…] *when one looks at either the functionality of biological solutions or the roads taken, then the choices are restricted, if not inevitable*"[8]. He points out that "[…] *at whatever level of biology one considers there will be loci of persistent biological stability that will act as irresistible attractors*"[8]. He introduces the concept of 'ecomorphs', defined as "[…] *recurrent anatomical configurations that answer the call of particular ecological needs*"[8]. He states that "*[e]very time the evolutionary process probes (or more likely discovers) a new era of biological hyperspace, the clade in question will find the novelty to be relative–because if evolution is a deterministic process, then each solution has a high probability of evolving several times*"[8]. "*[A] predictive framework*" of evolutionary history thus appears.[8] In the end, "[…] *the roads of evolution are indeed narrow and inevitable* […]"[8].

2.1.10. Contingency level of the universe

Gould himself states that, in his way of seeing things, "[…] *ultimately, the question of questions boils down to the placement of the boundary between predictability under invariant law and the multifarious possibilities of historical contingency. […]. I envision a boundary sitting so high that almost every interesting event of life's history falls into the realm of contingency*"[1]. Gould criticises Walcott for placing the boundary very low, according to his religious beliefs. Even if "traditionalist vision" and "religious interpretation" (or even religious fundamentalism) are closely related concepts, it seems to me quite possible to place the boundary very low without involving religious considerations, because considering the universe, in particular the living world, as being ruled by natural laws, and not by chance or contingency, appears to me to be just as well scientific, although unorthodox and generally rejected.

2.1.11. Science and laws of nature

Conventional, 'normal' science is based on a myth that most ideas are first really considered and seriously investigated before a number of them are rejected. First of all, it is important to mention that the reasons given for such a rejection are not necessarily valid. Secondly, it is clear that in some cases, hypotheses are discarded only because they are out of fashion or not well or not at all accepted by the scientific community. This is precisely what happened to the concept of Natural laws (or Laws of Nature) that would somehow guide or channel universal phenomena. Darwin himself briefly referred to 'laws of growth', and Grehan & Ainsworth remind us that "*[t]hese laws […] refer to a process which was responsible for the evolution of structure independent of natural selection*"[9]. In the same way, Shi V. Liu champions the idea that "*[e]volution is governed by some fundamental laws*"[10]. These natural laws form the basis of Richard Owen's structuralism, now advocated by Denton[11]. These laws have of course never really been investigated, as such a subject is considered prohibited and most scientists remain convinced that such laws do not exist. But what if they did exist?

According to Guillaume Lecointre and Pascal Picq, there is no evolutionary law. Even natural selection, which is basically differential reproduction, is not considered as a law, although it has all the characteristics of one.

For, indeed, what is a law?

The 2010 French Larousse dictionary defines a law as "*a general principle thought to determine things, people or the way a system works*";

1) e. g., Dicophilo[12] describes a scientific law as "*a regular pattern in the course of phenomena that, when formalised, makes it possible to predict them*";
2) The CNRTL[13] website presents a law of nature as "*a regular pattern in the course of events that enables the constants and rules which determine nature and its fundamental components to be deduced*";
3) The French version of Wikipedia presents the following sentence: "*A law of nature constitutes a manifestation of the principle of causality because, if the same cause always produces the same effect, things seem to be ruled by laws independently of a possible 'divine order' underlying them*"[14].

So, it appears that natural selection is indeed a natural law (and there are others). Strangely, scientists systematically deny the existence of any natural law in order to account for, namely, nature. In my opinion, this denial reveals an intellectual block. Indeed, to acknowledge that nature is governed by laws also means acknowledging the corollary idea that the Universe follows specific evolutionary paths precisely governed by these laws, a vision of things that is in blatant opposition to the Darwinian, random, unpredictable, and contingent conception of the world. For this reason, it seems preferable to simply exclude any such laws.

But in so doing, one moves from blocking to intellectual blindness. Are scientists not supposed to keep an open mind? Are they not supposed to study everything that is allowed by the terms of reference of science? Could it be that the laws of nature are so particular that they do not belong to science? Could it be that the universality of natural selection needs to be questioned? In my opinion, this problem is related to the confusion between the definition of a "law" (see above) and that of a "divine law", as if the use of laws necessarily led to religious thinking. We do not confuse "human laws" with "divine laws". Why should things be different with regard to the laws of nature? Just because these laws are not written down? Or because they remain elusive? Shouldn't we try to identify such laws, starting by recognising that a mechanism as universal as natural selection is indeed a natural law?

It should be possible to identify, among the natural laws, certain factors that actively or passively direct the evolutionary process, such as the many constraints that act on biological organisms: universal constraints, functional constraints, genetic constraints, developmental constraints, phylogenetic constraints.[15] Alibert et al. compare such constraints to "*barriers acting as evolutionary guides, which determine the direction of evolution*"[15]. They emphasise that "*these constraints mean that* not all evolutionary outcomes are equiprobable *and that the portion of the theoretical phenotypic space actually occupied by a lineage may be very limited*"[15] (my emphasis). However, certain constraints such as canalisation (a constraint acting on embryonic development by limiting the expression of genetic variation, leading to the conservation of the phenotype despite environmental changes) would play "*a significant role on the adaptive potential of organisms*"[15].

Erwin[6] also refers to constraints, mentioning "[…] *a limited range of solutions to a particular problem* [...]", hence "[…] *the limited range of viable solutions constrained the evolutionary history of different groups* […]", which leads to convergence. Erwin points out that "*[c]onstraints come in many forms, from those that limit the range of variation available for natural selection to act upon [...] to the physical forces of fluid dynamics, gravity and the like*". He quotes Kurt Schwenk, who distinguished two classes of constraints: "*For one class, the constraint operates because organisms simply are unable to produce new variants* […]"; "*The second class of constraint is one where there is abundant variation, but various forces act through natural* *selection to limit the range of solutions*". It is thus possible to see constraints as operating on the evolutionary process by making certain phenotypes mandatory and inevitable. From such a daring and undoubtedly promising perspective, it is quite possible that the decimation phases during major biological crises involve as yet unknown causes that are not in the least related to natural selection or chance. One or more natural laws could be involved, thus emphasising the inevitability of such decimations, especially as these crises seem to display common characteristics.

2.1.12. The "pattern of maximal early breadth" as a natural law

To explain the '*maximal initial proliferation*', Gould presents his model of '*maximal early breadth*', in relation to a maximal representation of the taxon just after its appearance in geological time. This simple and convincing model could be considered a natural law, firstly because "[…] *the pattern of maximal early breadth is a general characteristic of lineages at several scales and times* […]"[1]. Secondly, Gould states that "[…] *this "bottom-heavy" asymmetry may rank among the few natural phenomena imparting a direction to time*"[1]. Further on, he writes that "*[t]he early history of multicellular life is marked by a bottom-heavy signature for individual lineages* […]"[1] (of invertebrates with hard parts). Even better, this model constitutes "[…] *a general statement about the nature of evolutionary diversification*"[1], presented by Gould as "[…] *early experimentation and later standardization*"[1]. He concludes that "*[h]owever we interpret this bottom-heavy pattern, it strongly reinforces the case for contingency* […]"[1].

In this paragraph, I have a problem with the last sentence only. For it is indeed possible to conclude not that contingency is paramount, but to draw a fundamentally different, though entirely acceptable, conclusion. Gould's model actually possesses all the characteristics of a law, a natural law. In that case, the fact that many groups of living organisms (at least among metazoans) show early maximal proliferation would not be random at all, as this particular feature of evolution could be seen as a necessity, an evolutionary inevitability.

2.1.13. Orthogenesis

In relation with the Laws of nature and evolutionary constraints previously mentioned, Grehan & Ainsworth[9] come back to the notion of orthogenesis, often rejected because it is ill-defined and erroneously and simplistically interpreted as 'linear evolution', whereas it should be seen "[…] *as a process which involves an inherent tendency to vary in certain directions* […]", as well as the establishment of 'repetitive patterns'. This particular vision of evolution involves "[…] *an internal component that produces a tendency for evolutionary change without natural selection being required as a driving force*", thus "[…] *a directional change in variation which proceeds* regardless *of environment*"[9]. Liu[10] also considers that "*[e]volution is an ordered process* […]", 'highly directed' and 'highly non-random'. In such an original vision, orthogenesis can be considered as "[…] *a universal law of variation in a* few *definite directions […] that […] have nothing to do with utility*" and under the influence of which "[…] *the origin of variation is non-random* […]"[9]. This is a non-adaptive evolutionary mode (meaning adaptation does not intervene) that can lead to "[…] *'inevitable' extinction due to a limited evolutionary potential* […]"[9]. Therefore, "*[n]atural selection operates within the limits and directions set by orthogenesis so that structural form-making determines the kind of adaptation which is possible*".

The notion of evolutionary inevitability that I champion reappears in this unorthodox view of evolution. This inevitability is due, at least in part, to a fundamentally structuralist mechanism (not functionalist, the latter being at most secondary). For the involvement of intrinsic tendencies, preferred directions, repetitive patterns and a non-random origin stands strongly opposed to the evolutionary contingency advocated by Gould.

2.1.14. Argument from personal incredulity — Argument from credulity

At several points in his book, Gould makes his doubts clear about some explanations. For instance:

- "*We do not attempt to interpret the complex events of narrative by reducing them to simple consequences of natural law* […]"[1];

- "*We can explain an event after it occurs, but contingency precludes its repetition, even from an identical starting point*"[1];
- "*The modern order was not guaranteed by basic laws (natural selection, mechanical superiority in anatomical design), or even by lower-level generalities of ecology or evolutionary theory*"[1];
- "[…] *our planet has never come close a second time*"[1];
- "Homo sapiens *is an entity, not a tendency*"[1].

Here, in my opinion, Gould is seeking refuge in what Richard Dawkins calls his "*argument from personal incredulity*"[16]: because he cannot believe that something is real, he considers it to be false–and he is not alone with this view. This provides an opportunity to become aware of the psychological, and therefore also subjective, dimension of scientific research.

As opposed to Dawkins' argument of incredulity, I present the argument of personal (possibly collective) *credulity*. Because you believe that something is possible, you take it from the outset as self-evident, unmissable, and therefore true. According to me, most scientists rely on such reasoning, which leads to the implicit approval of statements that are never tested because they are never questioned (sometimes referred to as doxologies). When Gould draws his 'just history' from the reinterpretation of the Burgess Shale, he is totally caught up in my argument from personal credulity, taking along with him the entire scientific community, which seems to be as gullible as he is. But it could of course be said that structuralist inevitabilities also derive from personal credulity. How can we decide objectively? Will it ever be possible?

2.1.15. Science? Or science fiction?

Science investigates the world as it is, which is complex enough without trying to go any further. Imagining the world as it could have been is for me not science but science fiction, because it is possible to imagine anything and everything without providing any evidence, and because the hypotheses involved are totally unverifiable (typical cases of *ad hoc* assumptions). These are gratuitous statements of faith that cannot be falsified. It is therefore not science. As Gould himself says: "[…] *the pathways from this radically different starting point would have produced a world worthy of science fiction at its best*"[1]. He may claim that they are "[…] *honorable, reasonable […] alternatives* […]"[1], yet they are nonetheless science fiction. He goes even further, rightly noting that "*[t]he problem, of course, with describing alternatives is that they didn't happen* […]"[1], and that "*[t]he enumeration of unrealized worlds is a parlor game without end, for who can count the possibilities?*"[1]. He even acknowledges that "[…] *we could tell just as good a tale about the […] inevitable success*"[1] of the evolutionary process. He then asks: "*Did the current reign […] emerge by predictable necessity or contingent fortune?*"[1].

Reading this kind of argument made me realise how lucid Gould seems to be in the beginning, and then deliberately chooses the most conformist, orthodox conclusion, the most acceptable one to the scientific community as a whole. Indeed, from the evidence provided by Gould, the alternative explanation can also be chosen. Gould's inclination towards one option rather than the other is purely a matter of profession of faith. Besides, is it not interesting to wonder what would have become of the scientific world—and the world at large—had Gould decided to explain the world by natural laws ruling evolutionary inevitabilities?

2.1.16. A philological controversy?

The kind of controversy I am addressing here is sometimes considered as not authentically scientific, but only philological. Such reasoning would indeed be limited to nothing more than a literary-historical critical dimension, a mere 'document interpretation', or even only a 'word study'. I think, on the contrary, that such superficiality is only apparent, and that the analysis I propose is based on fundamental scientific grounds, as the following studies clearly show.

2.2. Revealing discoveries — Some aspects of evolutionary science at the beginning of the 21st century

Apart from the previous remarks, a number of studies carried out after Gould's death challenge his view of the evolution of life. Here are some of them.

2.2.1. Replaying the tape of life in the twenty-first century[17]

In this eloquently titled article, Virginie Orgogozo reveals that "[…] *a certain kind of predictability can emerge at higher levels over long time periods*". The author mentions that "[…] *the evolutionary process repeats itself at multiple levels, from molecules to ecosystems*". She points out that "[…] *given a set of environmental conditions, then certain types of phenotypes are expected*". She then comes up with the argument that "[…] *if the set of environmental conditions faced by living beings is known, then we may somehow, in some cases, predict the outcome in terms of phenotypic properties*". She states that "[…] *predictions are possible about the phenotypic and genotypic traits of evolving organisms*". Thus it seems that "[…] *evolution is more limited and more repeatable than expected*". Orgogozo concludes by suggesting that "[…] *evolution seems to follow a limited set of genetic and phenotypic paths at a given time point and space point during evolution*". Last but not least, "[…] *there are predictable portions within life's tape and [...] evolution might not be as unpredictable as once thought* […]", directly referring to Gould's statement.

2.2.2. Replaying the tape of life: quantification of the predictability of evolution[18]

In their article, Lobkovsky and Koonin state that "*[i]t is becoming clear that evolutionary trajectories in static correlated fitness landscapes are substantially non-random* […]". They conclude as follows: "[…] *evolution is strongly constrained and the part of the fitness landscape available for exploration is highly variable but typically small. Thus, if we actually could replay the tape of evolution, the outcome could have been considerably more similar to the existing diversity of life forms than Gould expected*".

2.2.3. Convergent evolution as natural experiment: the tape of life reconsidered[7]

In an article dealing with the tape of life, this time in relation to evolutionary convergence, Powell and Mariscal assert that "[…] *convergent evolution can constitute valid natural experiments that support inferences regarding the deep counterfactual stability of macroevolutionary outcomes*". They mention "[…] *iterated evolutionary outcomes that are probably common among alternative evolutionary histories and subject to law-like generalizations*". They claim that "[…] *certain design problems are pervasive in the history of life*" and that "[…] *the set of evolutionary solutions to pervasive design problems is highly circumscribed* […]". Specifically challenging Gould, they write: "*What contingency theorists like Gould reject is the proposition that the driving forces behind convergence often transcend the contingently entrenched developmental plans of particular lineages*". They even come to ask: "*Why should universal biochemical constraints on the evolution of form not be as interesting to biologists as the quirky, more detailed outcomes of evolution?*"

2.2.4. Historical contingency and the purported uniqueness of evolutionary innovations[19]

In this article, Geerat Vermeij affirms from the start that "[…] *important ecological, functional, and directional aspects of the history of life are replicable and predictable*". Referring to the idea that "*History, we are told, often repeats itself*", he notes that "[…] *many of the purportedly unique events in the early history of life result from the union, cooperation and integration of previously independent components*". He cautions that "*[t]he perception of uniqueness […] often arises from our tendency to ignore "failed experiments," closely similar or identical states that arose in minor (usually extinct) clades*". Vermeij comes to the idea that "*[m]ost innovations […] are expected to arise multiple times in many clades, because their adaptive benefits apply under a wide range of circumstances*". He boldly concludes: "[…] *few, if any, innovations are truly unique*". He finishes: "[…] *there is strong evidence from evolutionary convergences that the transitions are not random.*

[…] economic selection strongly favors some directions and some functional outcomes over others. These physical and economic realities therefore impart to history a certain predictability and replicability. By nudging dynamic systems toward some directions and outcomes, self-organization and selection set limits to the contingency of history".

2.2.5. The predictability of evolution: Glimpses into a post-Darwinian world[20]

In this article, Simon Conway Morris insists that "[…] *evolution is much more predictable than generally assumed* […]" and that "[…] *it is possible to identify a predictability to the process and outcomes of evolution*". He adds that "[…] *the evolutionary destinations […] are very far from being fortuitous* […]" and that "[…] *in reality rather than being an open-ended process evolution is deeply constrained*". Referring to "[…] *the uncanny capacity of organisms to navigate to particular solutions*", Conway Morris comes to the idea that "[…] *perhaps it is time we addressed biological properties per se if we want to bring some order to evolution rather than reiterate for the umpteenth time the dry bones of the Darwinian formulation*". So he concludes about "[…] *a biology that will move far beyond the Darwinian formulation* […]", especially because "[…] *evolution has an inevitable geometry* […]".

2.2.6. Contingency and determinism in evolution: replaying life's tape[21]

Based on empirical applications of Gould's 'crucial experiment' (which was originally only a thought experiment), the authors argue that "[…] *[Gould's] view of historical influences as the central feature of evolution remains debatable*". They also claim that "[…] *[Gould's] view that contingent effects were pervasive throughout evolution remains debatable*". Their criticism is motivated by a certain degree of repeatability that they have actually observed in the results of their experiments. Their conclusion is that "[…] *evolution can be both contingent and deterministic* […]", which conflicts with the high degree of contingency Gould advocated.

2.2.7. Convergence at the molecular level

Stunning molecular convergence

Perhaps the most surprising feature of evolutionary convergence is the fact that it is also found at the molecular level (proteins and even DNA). A striking example of protein convergence can be seen in two unrelated types of teleost fishes: Antarctic notothenioids and Arctic cods, which are used to living in ice-cold waters. These fishes synthesise antifreeze glycoproteins, enabling them to live in waters at a temperature slightly below −2 °C without their blood freezing. What appears as a surprise is that, although those fishes are not phylogenetically related, the glycoproteins they produce are almost identical. However, DNA sequences and gene substructure of the involved genes provide strong evidence that the antifreeze proteins in these two polar fishes in fact evolved independently.[22]

DNA convergence at various genetic and genomic levels

Given its most likely importance in the evolutionary process, molecular convergence has been intensively investigated in recent years. A central question is whether the convergence in phenotype reflects similar underlying molecular events. As a matter of fact, He et al. point out that convergence can happen at multiple levels of the genetic architecture[23]. Depending on the level of interest, genetic convergence occurs when the same gene has undergone many more amino-acid changes than expected; it can also be defined as the sharing of mutations in the same genes; it can also mean changes in the number of copies or the rate of evolution in the same genes[23]. Furthermore, it appears that the study of molecular convergence at the genomic level (including the convergence of biological pathways and changes in gene expression, gene copy number, amino acid usage, and whole-genome composition–sometimes co-occurring) helps to reveal the molecular basis of phenotypic convergence and provides insight into general principles of convergent evolution, such as the same amino-acid substitution in specific genes during adaptation to similar environments in extremophile plants[24].

Genomic convergence involving whole-genome duplications has also been linked to adaptation to extreme environments. Key genes implicated in stress response have indeed been shown to convergently maintain duplicated copies in diverse lineages. Xu et al. also notice convergent regulation of gene expression in distantly related conifers, stressing that convergence of gene expression may also be combined with convergence of variation in gene copy number[24].

Finally, the authors concentrate on the probability of genomic convergence in adaptation of extreme environments, stating that the convergence of genome-wide composition affects the majority of genomic sequences, making this a very widespread adaptive strategy in extremophile genomes, and one that is likely to have a relatively long-term perspective[24].

On the basis of all these results, it seems difficult not to consider genomic convergence as a first-order evolutionary process, imposing itself as an all-pervasive mechanism that might well be more important than natural selection in the evolutionary process as a whole.

Convergence vs. Natural selection

In most cases, convergent evolution is regarded as the clearest piece of evidence that adaptation has occurred[24]. In other words, observing that similar traits have repeatedly evolved is often taken as evidence that a trait is adaptive, particularly when there is a consistent match between trait and environment[25]. However, it might be asked whether convergent evolution does not reflect a common limitation to natural selection, which raises the possibility of other, more effective adaptive solutions. In this way, examining convergent evolution can help to unravel the many factors influencing adaptation. By going through the different levels of biological organisation, what might limit the action of natural selection can be highlighted, including a great number of constraints (genomic, genetic, developmental, and functional). This points out to specific modes of convergence, each one reflecting different limitations to evolution[25].

Fraser & Whiting identify numerous parameters likely to affect the probability of different modes of genetic convergence: the genomic context and its characteristics (pleiotropy, epistasis, mutation rate, number of beneficial mutations and distance to telomeres, GC content, repeat content, recombination rate), redundancy in the genotype-phenotype map, population history (i.e. founding bottlenecks and time since divergence or lineage age), effective population size, environmental characteristics (high dimensionality, multivariate similarities and divergences), and migration (gene flow). The authors point out that the non-random nature of at least some of these characteristics influences the probability of convergence, and that combinations of modes of molecular convergence are possible. The multidimensional nature of these mechanisms highlights the many limitations and constraints of the evolutionary process as a whole[25].

3. From the traditionalist (and comforting) view to the Darwinian (equally comforting) view to a new, post-Darwinian (also comforting?) view

According to Gould, Walcott's comforting traditionalist view (Gould makes use of several phrases of the kind, for instance "[⋯] a heart-warming-tale [⋯]", "[⋯] a comfortable and convenient view of life [⋯]", "[⋯] our standard and comfortable iconography [⋯]"[1]) was under the grip of deep-seated prejudices in his mind and time, such as the scale of beings, straight-line evolution (orthogenesis), the inescapable concept of progress and a high degree of predictability of evolution. In a way, this was not Walcott's fault: he could not but interpret the Burgess Shale using the science of his time, just as today's scientists apply the basic principles of modern science.

"*I do not think that any "higher" answer can be given, and I cannot imagine that any resolution could be more fascinating*"[1]: this is how Gould presents his modern view of contingency and, unlike Walcott's, this new interpretation of the world would be free of prejudices, preconceptions, and comfort, and thus would be of absolute scientificity. This more recent, more 'modern' view is implicitly presented as necessarily sound, unchallengeable and, in a sense, final.

With all the praise and respect I have for Gould, I think he is largely wrong.

He is wrong for several reasons:

1) Just like Walcott, Gould himself, seemingly unknowingly, is in the grip of a number of prejudices and preconceptions; he falls into the intellectual traps which he repeatedly exposes. The only difference is that they are not the same as for Walcott. Walcott believed in progress; Gould does not; Walcott believed in the predictability of evolution; Gould does not;
2) From a certain point of view, Gould's vision is also traditionalist, as it fits into the tradition of orthodox science at the end of the 20th century, i.e. a vision of the world in the grasp of chance, a contingent universe, in short, a vision that appears to be profoundly Darwinian. In a way, his conclusion about contingency could not have been different, and indeed was inevitable;
3) Grounding his view in contingency, Gould ignores the many evolutionary constraints mentioned above, which in one way or another shape the evolutionary process in a particular direction;
4) As seen earlier, starting from the same facts, from the same reinterpretation of the Burgess Shale, I have drawn an utterly different conclusion. Gould is clearly mistaken when he says that his own conclusion is the only one possible;
5) If Gould's conclusion is unchallengeable, then it is non-falsifiable in Popper's sense[26], and therefore unscientific. Such a solution is obviously dogmatic, and the one I propose seems to me to be markedly more moderate from this point of view;
6) As discussed above, Gould's "crucial experiment", the thought experiment in which the "tape of life" is "replayed" under different conditions, has been heavily criticised;
7) And finally, some of the Burgess Shale fossils have also been once more reinterpreted. As a result, the relationships between the ancestors of modern Arthropods have been clarified, and it appears that, according to David Williams, "[…] *Walcott was more correct than Gould thought*"[27]. For example, "*[a]lthough* Opabinia *initially defied assignment to any group of modern animals, it is now interpreted as lying [...] on the stem leading to the living arthropods*"[28]. Such revelations clearly call Gould's interpretation into question.

Is a new theory of evolution in the offing?[6] Erwin considers that the reflections and uncertainties about contingency and the evidence provided by convergence ought to lead to a new theory of evolution in the form of "[…] *an expansion that will include a more prominent role for the developmental genetics of evo-devo [...]. It will also include a greater appreciation for interesting biases in the generation of variation and possibly a role for a more hierarchical view of evolution* […]"[6].

As a post-Darwinian alternative, freeing us from the shackles of Darwinism, which is mainly based on chance and the pervasiveness of natural selection, the new interpretation I propose, which is more probable and realistic in the light of a number of discoveries, concurs with Erwin's proposal. It is very similar to the structuralist world view, which explains the major evolutionary innovations and attributes of living organisms not as Darwinian adaptations, but as fundamental natural principles governed by natural constraints and laws, in short as *evolutionary inevitabilities* as opposed to evolutionary flukes generated by environmental contingencies. Even if this world view, considered obsolete, has been discarded by the modern scientific community, this does not mean it is false, but only a minor theory in the face of a major one.

Considering the limitations of Darwinian functionalism, the many criticisms it has provoked, as well as the frustrations it has caused in the search for explanations of the evolutionary process,[29-35] it would not be surprising if in the future a true scientific revolution were to result in a new, more integrated paradigm, a new theory of evolution.

4. Overview and conclusion

Gould famously proposed a world view centred on the notion of contingency in the course of biological evolution. This interpretation of evolution has since been widely embraced by the Darwinian theory, according to which the major biological innovations of organisms are merely evolutionary flukes generated by environmental contingencies. In this essay, I have criticised this conclusion and provided a new interpretation of the history of life, based on the inevitability of evolution.

As a matter of fact, convergence, i.e. the rampant repetition of evolutionary occurrences, seems to be the rule rather than the exception. The driving forces behind convergence often transcend the contingently entrenched developmental plans of certain lineages. Moreover, an event can be described as unique because, in a given place and at a given time, it is necessarily bound to happen–it is inevitable. Certain factors must drive the evolutionary process, such as the many constraints that act on biological organisms (physico-chemical, functional, genetic, developmental, and phylogenetic constraints), together with important ecological, organisational, and directional aspects of the history of life that appear as replicable and predictable. As such, the implication of intrinsic tendencies, preferential directions, repetitive patterns, and a non-random origin, stands strongly opposed to the high-level evolutionary contingency advocated by Gould. The tape of life has a number of predictable sections. Evolutionary innovations arise from the implementation of basic and widely applicable principles–they derive from a fundamental and universal law. Ultimately, the paths of evolution appear to be narrow and inevitable.

The new interpretation I propose explains the major evolutionary innovations of organisms as fundamental natural principles governed by natural constraints and laws, in short as *evolutionary inevitabilities*. As a consequence, it has to be admitted that biology will have to move far beyond the Darwinian formulation, particularly because evolution has *an inevitable geometry*.

Conflict of interest

The author declares no conflict of interest.

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