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On the meaning of chance in biology

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Abstract

Chance has somewhat different meanings in different contexts, and can be taken to be either ontological (as in quantum indeterminacy) or epistemological (as in stochastic uncertainty). Here I argue that, whether or not it stems from physical indeterminacy, chance is a fundamental biological reality that is meaningless outside the context of knowledge. To say that something happened by chance means that it did not happen by design. This of course is a cornerstone of Darwin's theory of evolution: random undirected variation is the creative wellspring upon which natural selection acts to sculpt the functional form (and hence apparent design) of organisms. In his essay *Chance & Necessity*, Jacques Monod argued that an intellectually honest commitment to objectivity requires that we accord chance a central role in an otherwise mechanistic biology, and suggested that doing so may well place the origin of life outside the realm of scientific tractability. While that may be true, ongoing research on the origin of life problem suggests that abiogenesis may have been possible, and perhaps even probable, under the conditions that existed on primordial earth. Following others, I argue that the world should be viewed as causally open, i.e. primordially indeterminate or vague. Accordingly, chance ought to be the default scientific explanation for origination, a universal 'null hypothesis' to be assumed until disproven. In this framework, creation of anything new manifests freedom (allowing for chance), and causation manifests constraint, the developmental emergence of which establishes the space of possibilities that may by chance be realized.

Keywords

Evolution; Development; Freedom; Constraint; Knowledge

"Our world of propensities is inherently creative" - Karl Popper (1990: 20)

"In the fields of observation chance favors only the prepared mind" - Louis Pasteur (1854)¹

Introduction

In biological discourse, as in colloquial usage, *chance* refers either to happenstance (as in 'it happened by chance'), or indeterminate possibility (as in 'it has a chance of happening'); i.e., that which is random, fortuitous, or accidental by virtue of being unpredictable,

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¹(December 7, 1854) Lecture, University of Lille

unforeseen, or unintended. Although the word *chance* means different things in different contexts, it invariably implies the potential for surprise. Any event that can be described as happening by chance has some capacity to surprise us. That is true whether the chance event reflects a fundamental irregularity or fluctuation in the world (ontological chance) or simply our own lack of knowledge (epistemological chance). Chance also invariably implies possibility, as only that which is possible can be said to have a chance of happening. In this paper I use the word *chance* in as general sense as possible, eschewing definitions that would serve to focus the argument on one or another specific meaning. Although this may run the risk of equivocation, it is consistent with common usage, both in biological and colloquial discourse, wherein the word is seldom if ever defined and its various meanings are amalgamated. My hope is that what I mean each time I use the word *chance* will emerge from the context, and that the reason for my taking this tack will come clear by the end of the essay.

The human predilection for control is born of our animal needs, which compel us to work purposefully in an endeavor to direct the course of events toward desired ends. Ideally this requires that we ‘leave nothing to chance’. For in human engineering, *chance* refers to the world of unknown possibilities whose realization might thwart the realization of our purpose, and as such is something to be avoided. It is widely assumed that this can be accomplished via sufficient knowledge and planning, i.e. by way of *intelligent design* that eliminates or reduces the number of unknown contingencies. Pragmatically speaking, acquiring sufficient knowledge is the purpose of science.

Colloquially then, *chance* refers to that which is unpredictable, ostensibly by virtue of insufficient knowledge. Any outcome that may or may not by chance occur is *uncertain*, i.e. cannot be predicted with certainty. This raises a fundamental yet remarkably contentious question: is it ever possible to ‘leave nothing to chance’, and thus foresee the future with certainty? In the early nineteenth century the astronomer and mathematician Pierre-Simon Laplace opined that in principle it should be. But soon thereafter the discovery of the second law of thermodynamics began to erode that hope, by showing that no work toward a desired end can ever be 100% efficient, no matter how much knowledge is applied to make it so. And a century later the hope was further dashed by Werner Heisenberg’s discovery that the minimum information necessary for precise prediction of a quantum particle’s trajectory—position and momentum—cannot possibly be obtained, as measuring one precludes measuring the other. Finally, the late twentieth-century discovery of mathematical chaos laid to rest the idea that the future can be predicted based on knowledge of the present.

And yet, the debate continues as to whether chance, at least as most of us experience it, is ontological or ‘merely’ epistemological. One reason for this is that it is widely held that Heisenberg’s uncertainty principle applies only to quantum phenomena, whereas (owing to statistical averaging) macro-scale phenomena obey Newton’s deterministic laws of motion (or more generally, Einstein’s Theory of Relativity) and are thus in principle predictable. Chaos, produced by mathematically deterministic dynamics, is unpredictable only because it is not possible with currently conceivable technology to obtain sufficiently accurate measurements (i.e. knowledge) of the ‘initial’ (and in the real world, contextually complex and ever-changing) conditions upon which the specific outcomes of those dynamics depend.

And the second law of thermodynamics is a determinative law of physics insofar as, barring interference, it directs predictable trajectories of change: diffusion, erosion, melting, and even the self-organizing development of dissipative structures (Prigogine 1978; Salthe 1993; Deacon 2011). Thus some may still argue that with enough knowledge and sufficiently advanced technology we ought to be able to intelligently design a future that leaves, if not nothing, then little (or at least, little ‘of consequence’) to chance.

I submit that this is a dangerous (and at this stage of human history, even delusional) assumption that lacks empirical support (Coffman and Mikulecky 2012). Even if we choose to believe that chance is nothing more than an expression of epistemological limits, the three post-Enlightenment scientific discoveries mentioned above all clearly indicate that the knowledge required to ‘leave nothing to chance’ *cannot possibly* be acquired. Therefore the most reasonable (or at least, the most useful) interpretation is that, whether or not it derives from processes that follow deterministic laws, chance is a fundamental, unavoidable reality. This ought to be viewed as a good thing: for if it were not so then we would not be here to ponder the seeming improbability of our own existence. Moreover, as chance manifests not only in accidents, but also in (what we perceive as) miracles, it may well be the only realistic source of hope in our rapidly degenerating world (see Wheeler, this issue). To see this we first consider the idea that placed chance firmly at the center of biological thought: Darwin’s theory of evolution by means of natural selection (Darwin 1859).

The central role of chance in Darwinian evolution

A key observation upon which Darwin founded his theory is that there is a good deal of phenotypic variation in any natural population of a species. Although this in itself was not news, Darwin was a keen naturalist, and after many careful observations came to the conclusion that the variation was random, not directed toward any discernible end—that is, phenotypic variation in a population is an expression of chance rather than of purpose (be it Divine, or merely a natural consequence of the purposeful ‘use and disuse’ of anatomy by individual organisms striving to adapt to their environment, as Lamarck had theorized). The evolution of (what appear to us to be) extraordinarily well-designed organismal adaptations, e.g. a wing or an eye, was then directed entirely by the increased *chances* for reproduction that the hereditary lottery afforded the lucky recipients of beneficial traits.

Today Darwin’s heretical interpretation of nature’s variety continues to rankle. On the one hand, it motivates legitimate studies of evolutionary developmental biology (Evo-Devo), which seek to elucidate the extent to which (contra Darwin) phenotypic variation actually *is* directed, by ontogenetic self-organization (Arthur 2002). On the other hand it spurs those who continue to argue for ‘intelligent design’ (ID), the age-old claim that the exquisitely adapted designs manifested by living systems—their ‘irreducible complexity’ (epitomized by physically arbitrary yet algorithmically prescriptive information encoded in the genetic apparatus; Abel 2008)—could not possibly have originated by chance. But that argument amounts to sophistry (e.g. Hoyle’s Fallacy; Gatherer 2008), as it *presumes* adequate knowledge of (the limits on) the space of possibility. That is, it presupposes that current knowledge provides an accurate, unbiased statistical account of, or means of determining, what may or may not by chance happen.

Ironically, this presumption originated in Enlightenment science (Coffman and Mikulecky 2012), which helps explain the odd fact that some ID proponents are professional scientists. But proponents of ID aren't the only ones who presume to know: some ardent atheists argue, ostensibly with support from science (echoing Laplace) that fate is fully pre-determined by physical causation (i.e., whatever happens in the universe is physically *forced* to happen, so in reality there is no such thing as freedom or free will). Thus, in the culture war between religious 'creationists' and atheistic 'evolutionists', the protagonists on both sides agree on the terms: the premise that the perception of chance (at least at non-quantum scales) is an *illusion*, created by ignorance of the causes that inexorably direct the unfolding of destiny. The fight then is over what those causes are (mindlessly physical or mindfully supernatural), and who is the more ignorant, with each side believing it to be the other. No one questions the assumed premise of causal closure itself.

But if (and to the extent that) Darwin is right, they should. For according to Darwin, copious *undirected* variation is the creative wellspring that affords evolutionary potential. From this perspective it should be expected that the potential for evolution (i.e. the capacity to *change*) would be reduced by anything that limits chance. This would include not only design (intelligent or otherwise), but also physical forces, or more generally, developmental (developed informational) constraints. Hence, it would also include presumed knowledge.

Monod's *Chance & Necessity* and the origin of life

In *Chance and Necessity: Essay on the Natural Philosophy of Modern Biology*, Jacques Monod argued that the discoveries of molecular biology thoroughly vindicate Darwin by providing the mechanism of heredity that was the major knowledge gap in his theory (Monod 1971). In his essay Monod (p. 21) chastised biologists who don't concede that organisms do in fact act purposefully ("projectively"), wherein lies "a flagrant epistemological contradiction" (to the scientific "principle of objectivity") that Monod sees as "the central problem of biology". What accounts for the purposefulness of organisms, according to Monod, is the naturally selected hereditary mechanism that Darwin was not privy to—the inherited information (memory) encoded in the nucleotide sequence of DNA, which in the context of a living cell not only specifies the functional structure of proteins (including enzymes, the "Maxwell's Demons" of the cell), but also the information needed for their appropriate deployment under the range of circumstances that a cell normally encounters. Monod pointed out that this information was completely arbitrary with respect to the laws of physics and chemistry, and therefore was not predictable from those laws. In other words, biology, unlike physics and chemistry, is a *special* science concerned with functional information, i.e. information that is *useful* to organisms, and hence contextually meaningful. Monod, following Ernst Mayr, refers to this as *teleonomy*.

But if physics and chemistry do not account for such information, how can we explain its origin? According to Monod, for anyone committed to the principle of objectivity (as every scientist ought to be), the only honest answer is that it originated by chance. In other words, we don't know how it originated.

Will we ever? Monod avers that it is possible we may not, as we may never be able to sufficiently elucidate or reconstruct the particular circumstances that produced the first living (which according to Monod means genetically-informed) cell. But this lack of relevant information does not mean that life could not have arisen by chance. On the contrary, honest commitment to the principle of objectivity requires that we accept that it did, however slim the chance may have been. This is, in fact, Monod's central point:

Life appeared on earth: what, **before the event**, were the chances that this would occur? The present structure of the biosphere far from excludes the possibility that the decisive event occurred **only once**. Which would mean that its **a priori** probability was virtually zero.

This idea is distasteful to most scientists. Science can neither say nor do anything about a unique occurrence. It can only consider occurrences that form a class, whose **a priori** probability, however faint, is yet definite.² Now through the very universality of its structures, starting with the code, the biosphere looks like the product of a unique event. It is possible of course that its uniform character was arrived at by elimination through selection of many other attempts or variants. But nothing compels this interpretation.

Among all the occurrences possible in the universe the **a priori** probability of any particular one of them verges upon zero. Yet the universe exists; particular events must take place in it, the probability of which (before the event) was infinitesimal. At the present time we have no legitimate grounds for either asserting or denying that life got off to but a single start on earth, and that, as a consequence, before it appeared its chances of occurring were next to nil.

Not only for scientific reasons do biologists recoil at this idea. It runs counter to our very human tendency to believe that behind everything real in the world stands a necessity rooted in the very beginning of things. Against this notion, this powerful feeling of destiny, we must be constantly on guard. Immanence is alien to modern science. Destiny is written concurrently with the event, not prior to it. Our own was not written before the emergence of the human species, alone in all the biosphere to utilize a logical system of symbolic communication. Another unique event, which by itself should predispose us against any anthropocentrism. If it was unique, as may perhaps have been the appearance of life itself, then before it did appear its chances of doing so were infinitely slender. The universe was not pregnant with life nor the biosphere with man. Our number came up in the Monte Carlo game. Is it any wonder if, like the person who has just made a million at the casino, we feel strange and a little unreal? (Monod 1971: 144–146; emphasis in original)

In other words, our universe produces untold numbers of unique events that, if we wish to remain objective, can only be described as chance occurrences, i.e. events that are simply not predictable *a priori* no matter how much scientific knowledge we have (see Auletta and Torcal, this issue). These would include things as trivial (and physically deterministic) as the outcome of a particular coin toss, or of a role of the dice, or of a Monte Carlo game.

²See discussion in Auletta and Torcal, this issue.

According to Monod the origin of life should also be viewed as such an occurrence, and as such, as scientifically intractable (i.e. unpredictable) as any other chance event.

But that does not mean that science cannot *explain* the origin of life *in principle*, e.g., by elucidating formal criteria that would have been necessary (and perhaps even sufficient) for it to happen, and asking what the chances are that those criteria were met by the conditions on primordial earth. It only means that science cannot determine with certainty that they were met, or that they actually do account for life's origin. Thus:

In saying that as a class living beings are not predictable upon the basis of first principles, I by no means intend to suggest that they are not **explicable** through these principles—that they transcend them in some way, and that other principles, applicable to living systems alone, must be invoked. In my view the biosphere is unpredictable for the very same reason—neither more nor less—that the particular configuration of atoms constituting this pebble I have in my hand is unpredictable. No one will find fault with a universal theory for not affirming and foreseeing the existence of this particular configuration of atoms; it is enough for us that this actual object, unique and real, be **compatible** with the theory. This object, according to the theory, is under no obligation to exist; but it has the right to.

That is enough for us as concerns the pebble, but not as concerns ourselves. We would like to think ourselves necessary, inevitable, ordained from all eternity. All religions, nearly all philosophies, and even a part of science testify to the unwearying, heroic effort of mankind desperately denying its own contingency. (Monod 1971, 41–44; emphasis in original)

So, if life originated by chance (and any scientist committed to the principle of objectivity must be open to the possibility that it did), the question becomes: what *was* the chance (i.e. probability) that it would originate under the conditions present on primordial earth? Was it virtually nil as Monod suggests? Or might it have been pretty good? To answer those questions it is useful to consider that, in general, the opportunities afforded by chance depend on the space of possibility delimited by a constraining context, whose parameters are established by a complex system that develops into existence (and ultimately, into senescence; Salthe 1993). As discussed below, the chance for any specific thing therefore changes over time, and may either increase or decrease (possibly to nil) with development of a given *system*. It is interesting to note that, to the extent that this is so, the uniformitarian assumption invoked by Darwin is violated.

For instance: in the beginning, the environment on earth (and hence the geochemical processes underway and the opportunities that they afforded) was in fact very different than it is today. Geochemical paleontology indicates that early in its development the earth had a reducing atmosphere. Combined with the geothermal organic chemistry similar to that found in deep sea vents of today, that would have likely been conducive to development of a pre-biotic chemical ecosystems (or 'metabolisms') based on the reductive (reverse) tri-carboxylic acid (TCA) cycle (Smith and Morowitz 2004). Such a system could by chance have generated many of the precursors of modern biochemistry, including RNA (Copley et al. 2007), the likely antecedent of the modern genetic system of information storage.

However, the hard question remains: how could such a system have created the first ‘epistemic cut’ (Pattee 2001) between *knower* and *known* (or equivalently, between subject and object) that is arguably the defining feature of life itself, and which is embodied in the genetic system present in all known forms of life?

We still do not know the answer to that question, so all we can say is that for all we know it happened by chance. That being said, we can still ask what would have had to occur, and develop testable scenarios for how those things might have happened.

And indeed, significant progress is being made on that front, both conceptually and experimentally. For example, on the experimental side Katarzyna Adamala and Jack Szostak recently showed that RNA-directed RNA synthesis can occur in fatty acid vesicles in the presence of citrate (Adamala and Szostak 2013). This was a breakthrough discovery, because fatty acid vesicles disintegrate in the presence of free Mg^{2+} , an essential cofactor for RNA synthesis. *A priori* this appeared to significantly reduce if not eliminate the chance that RNA synthesis could have occurred within fatty acid vesicles, which are the most plausible precursor to membrane-bound cells (‘protocells’). By chelating Mg^{2+} , citrate protects the vesicles from disintegration while still allowing for RNA synthesis. With this new knowledge we learn that fatty acid proto-cells capable of nucleic acid reproduction had a much higher chance of forming spontaneously than previously thought.

On the conceptual side, Terrence Deacon recently proposed an intriguing model, originally termed an ‘autocell’ (Deacon 2006) and recently renamed ‘autogen’ (evocative of ‘autogenesis’; Deacon 2011). An autogen is a hypothetical construct consisting of an autocatalytic set of chemical reactions that produces macromolecules that self-assemble into enclosed containers. The key to autogenesis is the chance reciprocal coupling of complementary *needs*—essentially constituting a minimal ecology. To be sustainable, the autocatalytic set needs a limit on diffusion, which is provided by the container. To self-assemble, the container needs components, which are provided by the autocatalytic set. Thus, in the context of an autogen, the chances for both autocatalysis and self-assembly are significantly increased.

Insofar as the autogen is a stable structure, it is a ‘homeostatic’ time capsule afforded increased chances of surviving periods of resource depletion. Insofar as it is not strictly dependent on the *specific* identity or structure of its components, only their ability to function in autocatalysis and self-assembly (i.e., its structure is indeterminate with respect to function), it is afforded chances for evolving. The autogen (however constituted) thus constitutes a minimal self-entailing, evolvable system. While it does not create (much of) an epistemic cut, it does create increased potential for one: for, by manifesting a physically bounded, enduring *self* with defined needs, the autogen represents a constrained space of possibility that selectively favors within itself any random, heritable change that by chance produces a semiotic entailment structure (inferential model) that allows it to ‘anticipate’ those needs, by working projectively (purposefully) toward their fulfillment *before* they become an existential emergency. It thus provides an evolutionary step toward the ‘anticipatory systems’ of Rosen (Rosen 1985; Louie 2010), and a primeval precursor to the ‘prepared mind’ of Pasteur.

The dynamics of chance in the development of complex systems

Most fundamentally, *chance* refers to mere possibility. Whatever is impossible has no chance (which is why chance favors only the prepared mind, i.e., the mind that has been developmentally opened to specific possibilities). For anything that *is* possible, the chance (and hence probability) that it will happen depends on the context. Within a given context, some possibilities may be afforded a better chance than others. Following arguments articulated by Elsasser (e.g. Elsasser 1972), Ulanowicz (2009) has noted that given its immense combinatorial complexity, our universe affords an immense number of physically conceivable possibilities, most of which have virtually no *a priori* chance of occurring, just as Monod argued may be the case for the origin of life. However, a conceivable possibility may or may not actually be possible, depending on the organizational constraints of the world (Juarrero 1999).

But how do we ever know whether a conceivable possibility is actually possible? In reality there is only one way, which is to witness the possibility become actuality. This is in fact the basis of the scientific method of empirical verification. If we witness something, then we know that it is possible, which means that it may happen again. If we are scientists then we may try to make it happen again in the context of an experiment, that is, we may try to reproduce the result. If we cannot, then our peers will likely remain skeptical about the very possibility.

I contend that the concept of chance, to the extent that it represents anything *real*, is inherently epistemological, as it invariably implies (the possibility of) knowledge. So from a pragmatic standpoint, the metaphysical question alluded to above—of whether chance is ontological or ‘merely’ epistemological—is absurd, because outside the mental context of knowledge it is impossible to conceive, much less evaluate, the space of possibility. This perspective inverts the relationship usually assumed to obtain between ontology and epistemology. Simply said: without knowledge, chance is a meaningless concept.

By extension, we can say that the meaning of chance in biology depends entirely on the state of biological knowledge. With respect to the origin of life question discussed above, this manifests in the possibility that, what Monod surmised to have virtually no chance of happening (based on his limited knowledge) may eventually be viewed, in the context of increased knowledge produced by science, to be virtually inevitable.

Insofar as chance implies knowledge, it implies semiosis. Within Peirce’s triadic system of categories it signifies ‘Firstness’. But it only does so via actual occurrences (signifying ‘Secondness’) that elicit a *generalizing* interpretation within a system of interpretance (signifying ‘Thirdness’), which creates knowledge (see Ostdiek, this volume). That is, chance is fully realized only via the act of interpretation, which integrates all three categories within a body of (embodied) knowledge.

In Peirce’s system, any possibility that does not come of necessity is afforded by vague, innate tendencies of the universe, which are essentially equivalent to the ‘propensities’ of Karl Popper (Popper 1990). Insofar as any actualized tendency promotes its own repetition, persistence, and/or maintenance (e.g., by way of positive feedback, as in an autocatalytic

cycle), it tends to become a *habit*. The transformation of a tendency (or propensity) into a mature habit occurs via *development* (growth and self-organization), essentially by way of the phenomenology articulated by Ulanowicz (Ulanowicz 1986, 1997; Coffman 2006; Ulanowicz 2009) and Salthe (1993). In this scheme information manifests prior development (Coffman 2011a), and any form of knowledge can then be said to be the product of an *anticipatory* habit emerging from a congruent relation that develops between an embodied system of interpretance with rapid dynamics (e.g. an organism, or a cell) and its more slowly changing environment (von Uexküll's 'Umwelt'—Salthe, this issue), i.e., what Robert Rosen referred to as a modeling relation (Rosen 1985, 1991; also discussed by Salthe 1993).

According to Rosen, anticipation via the modeling relation occurs when a system *encodes* information provided by its environment, then determines by some internal interpretive system (e.g. a set of biochemical pathways) what that encoded information *entails* (or 'means'), then creatively *decodes* the entailment into an activity. A model is realized if the internally entailed activity of the system is predictive of an external chain of causation, allowing the system to anticipate environmental changes before they occur. For this to work it is clear that two things must hold true: the environment must behave in a somewhat predictable (i.e. habitual) fashion, and the system must have some sort of stable memory of that behavior that underpins its interpretive system. Since the system also needs its memory to interpret present experience, it can be said that living systems "experience the present and anticipate the future by living in the past" (Coffman and Mikulecky 2012: 88). To the extent that this is true, our awareness of the space of possibility is always limited to what has happened in the past, and thus unable to judge the possibility of events that may be possible, but have never occurred. The modeling relation is therefore not able to anticipate unique events, or even effectively deal with the uniqueness of each event (see paper by Auletta and Torcal, this issue).

On the other hand, habitual activities informed by the modeling relation continuously create new opportunities (i.e., by way of their impact on the environment), altering the space of possibility by providing new affordances as well as new constraints that are linked to a growing body of knowledge. Knowledge thus plays a role (intentional or not) in determining both the chances of something happening, and what we apprehend as happening or having happened by chance (see paper by Salthe, this issue).

In this perspective the universe is best viewed as being causally open (or alternatively, perhaps even fundamentally 'a-causal', insofar as there may be spontaneous events that have no cause at all). If nothing else, this simply acknowledges the practical benefits of being open-minded (which is to say maximally unbiased, i.e. objective, as per Bacon's Idol-free ideal) about causation. To say that something happens by chance simply means that we don't *presume to know* what caused it to happen (although we may know or have an inkling of some of the contributing causes, ideally representing all four Aristotelian categories; Coffman 2011b)—leaving open the possibility even that it was not caused at all. As argued by Monod, this is in fact the most objective position that can be taken, and thus the one that we ought to take if we want to use science as a pathway to knowledge.

Thus, if we hypothesize that a given event did *not* occur by chance, but rather was directed by a specific causal mechanism, then any test of that hypothesis must disprove the alternative ‘null’ hypothesis that the event can be expected as a random occurrence. Toward that end it behooves us to be knowledgeable about the ‘common patterns of nature’ (Frank 2009): the types of probability distributions expected purely by chance given a specified set of constraints, and the information about underlying process imparted by any deviations from those distributions. This approach has for example been fruitfully applied to the question of whether global patterns of gene expression (a stochastic process at the level of single molecules and cells) are generated by global or gene-specific constraints (Sanchez and Golding 2013).

The premise that origination entails (openness to) chance makes sense of what is otherwise merely a curious fact that has emerged over the past few decades from molecular studies of developmental biology: viz., the ubiquity of repression (or inhibition) in the genesis of organismal form. For example, it is not uncommon to find that spatially localized gene activation during embryogenesis occurs via localized repression of global repressors. Localized inhibition is also key to epigenesis via Turing-type reaction-diffusion dynamics, which transform stochastically fluctuating, nearly homogeneous primordia into predictable, well-defined patterns. In general, spatiotemporal epigenetic controls during development serve to shut down (what is otherwise noisy) gene expression, e.g. by way of DNA methylation. Thus, it appears that in organismal development, immature stages with high regenerative capacity are generally more open to chance expression of genomically encoded information. With the advent of modern DNA sequencing technology this can now be readily tested by quantifying the informational entropy of the transcribed genome (‘transcriptional entropy’) (Coffman 2011a). Although this approach has not yet been widely applied, the prediction is that when it is, it will show that cell differentiation invariably entails a progressive reduction of transcriptional entropy.

Similar phenomenology also obtains in systems at higher levels of organization (such as ecosystems and human economies; Ulanowicz 1986, 1997, 2009; Coffman 2006, 2011a), in which development results in progressively constraining circumstances that reduce the degrees of freedom (i.e. diversity of chances) afforded players within the system. This freedom is afforded by activities, interactions, or relations that, with respect to the projective work being done by the larger system, are relatively unproductive, and hence less constrained and more open to chance—what Ulanowicz refers to as system ‘overhead’. Development to senescence (whether it be in an organism, an ecosystem, or economy) is characterized by loss of overhead (leaving nothing to chance!), which places the system in an inflexible, metastable state of jeopardy. In an organism, overhead is provided by (among other things) pluripotent stem cells. In an ecosystem it is provided by trophically redundant species diversity and generalist species. In a modern industrial economy it is provided by community, art, science, and small farms and businesses. In short, the plasticity and hence sustainability of a system depend on it remaining open to chance.

Finally, given that any kind of systemic development entails projective work, it behooves us to ask what the second law of thermodynamics means *vis-a-vis* the dynamics of chance. The inefficiency demanded by the second law can reasonably be interpreted as being

necessitated by chance occurrences that invariably accompany any work directed toward a specific end, resulting in cross-purpose friction. Such chance occurrences manifest the brute fact that reality (the actual world) is never ideal (i.e., is never entirely congruent with our projective model of the world). Other manifestations of the second law, such as diffusion and melting, can also be interpreted as expressions of chance, insofar as they are changes that occur *spontaneously* (i.e. are not forced from the outside) in the absence of interfering constraints that specifically prevent their occurrence. But the second law also ensures that nothing can ever be completely constrained, making it impossible to leave nothing to chance. As noted by Monod:

Evolution in the biosphere is therefore a necessarily irreversible process defining a **direction in time**; a direction which is the **same** as that enjoined by the law of increasing entropy, that is to say, the second law of thermodynamics. This is far more than a mere comparison: the second law is founded upon considerations **identical** to those which establish the irreversibility of evolution. Indeed, it is legitimate to view the irreversibility of evolution as an expression of the second law in the biosphere. (Monod 1971: 123; emphasis in original)

The second law can be generally interpreted as meaning that any intentional work will have *unintended consequences*. The silver lining is that, in systems that are far from thermodynamic equilibrium, those unintended consequences generally afford chances (Peircean tendencies, Popperian propensities) for new developmental trajectories. And, when they occur within systems that have developed to the fragile, metastable end-state of senescence, the chances for the eventual maturation of completely new (as yet vague, indeterminate) systems are often increased (Coffman 2006). To the extent that this law of nature is widely *known*, it can be incorporated into an anticipatory inferential model, and thus used to increase the chance of averting (or at least being better prepared for) disaster. Of course, since the anticipatory efficacy of any model depends on habits (selected encodings and entailment structures, and their habitual realization in the world) developed by way of past experience, the adaptive affordances of such models will tend to diminish in thermodynamically destabilized environments, such as that of contemporary earth. In such circumstances, chance assumes an increasingly prominent role as the global rate of change accelerates, and day-to-day events become decreasingly predictable (more surprising) as the predictability of the final catastrophic outcome increases.

Conclusion

From Darwin on, the central lessons of biology have been that life is a game of chance and causation is a matter of context. Chance signifies possibility, and thus freedom to create. Causation signifies selectively constraining habits that eliminate degrees of freedom to act in some ways, while affording chances (freedom) to act in new ways. Constraint begets necessity, which emerges developmentally in self-organizing systems that are ultimately constrained (and hence directed) by (needs, such as for food, demanded by) the second law of thermodynamics. By decreasing the chances afforded some things, the second law increases the chances afforded others, along an irreversible, specifically unpredictable but generally predictable evolutionary trajectory.

References

- Abel DL. The 'cybernetic cut': progressing from description to prescription in systems theory. *Open Cybernetics & Systemics Journal*. 2008; 2:252–262.
- Adamala K, Szostak JW. Nonenzymatic template-directed RNA synthesis inside model protocells. *Science*. 2013; 342:1098–1100. [PubMed: 24288333]
- Arthur W. The emerging conceptual framework of evolutionary developmental biology. *Nature*. 2002; 415:757–764. [PubMed: 11845200]
- Coffman JA. Developmental ascendancy: from bottom-up to top-down control. *Biological Theory*. 2006; 1:165–178.
- Coffman JA. Information as a manifestation of development. *Information*. 2011a; 2:102–116.
- Coffman, JA. On causality in nonlinear complex systems: the developmentalist perspective. In: Hooker, C., editor. *Handbook of the Philosophy of Science: Philosophy of Complex Systems*. Vol. Vol. 10. Elsevier; New York: 2011b. p. 287-309.
- Coffman, JA.; Mikulecky, DC. *Global Insanity: How Homo sapiens Lost Touch with Reality while Transforming the World*. Emergent Publications; Litchfield Park, AZ: 2012.
- Copley SD, Smith E, Morowitz HJ. The origin of the RNA world: Co-evolution of genes and metabolism. *Bioorganic Chemistry*. 2007; 35:430–443. [PubMed: 17897696]
- Darwin, C. *On the Origin of Species by Means of Natural Selection*. Murray; London: 1859.
- Deacon TW. Reciprocal linkage between self-organizing processes is sufficient for self-reproduction and evolvability. *Biological Theory*. 2006; 1:136–149.
- Deacon, TW. *Incomplete Nature: How Mind Emerged from Matter*. W. W. Norton & Co.; New York: 2011.
- Elsasser WM. A model of biological indeterminacy. *Journal of Theoretical Biology*. 1972; 36:627–633. [PubMed: 5080452]
- Frank SA. The common patterns of nature. *Journal of Theoretical Biology*. 2009; 22:1563–1585.
- Gatherer D. Finite universe of discourse: the systems biology of Walter Elsasser (1904-1991). *The Open Biology Journal*. 2008; 1:9–20.
- Juarrero, A. *Dynamics in Action: Intentional Behavior as a Complex System*. MIT Press; Cambridge, MA: 1999.
- Louie AH. Robert Rosen's anticipatory systems. *Foresight*. 2010; 12:18–29.
- Monod, J. *Chance and Necessity: An Essay on the Natural Philosophy of Modern Biology*. Vintage; New York: 1971.
- Pattee HH. The physics of symbols: bridging the epistemic cut. *Biosystems*. 2001; 60:5–21. [PubMed: 11325500]
- Popper, KR. *A World of Propensities*. Thoemmes; Bristol: 1990.
- Prigogine I. Time, Structure, and Fluctuations. *Science*. 1978; 201:777–785. [PubMed: 17738519]
- Rosen, R. *Anticipatory Systems: Philosophical, Mathematical and Methodological Foundations*. Pergamon Press; Oxford: 1985.
- Rosen, R. *Life Itself: A Comprehensive Inquiry into the Nature, Origin, and Fabrication of Life*. Columbia University Press; New York: 1991.
- Salthe, SN. *Development and Evolution: Complexity and Change in Biology*. MIT Press; Cambridge, MA: 1993.
- Sanchez A, Golding I. Genetic determinants and cellular constraints in noisy gene expression. *Science*. 2013; 342:1188–1193. [PubMed: 24311680]
- Smith E, Morowitz HJ. Universality in intermediary metabolism. *Proceedings of the National Academy of Sciences U S A*. 2004; 101:13168–13173.
- Ulanowicz, RE. *Growth and Development: Ecosystems Phenomenology*. Springer-Verlag; New York: 1986.
- Ulanowicz, RE. *Ecology, the Ascendent Perspective*. Columbia University Press; New York: 1997.
- Ulanowicz, RE. *A Third Window: Natural Foundations for Life*. Templeton Press; West Conshohocken, PA: 2009.