Available online at www.sciencedirect.com
ScienceDirect
Current Opinion in
Systems Biology

The tripartite nature of causalities in ecosystem dynamics

Robert E. Ulanowicz[1,2]

Abstract

Recent opinions on ecosystem dynamics point away from the conventional notion that changes in ecosystems result only from the action of mechanisms interacting with blind chance. More recently, ecological outcomes have come to appear rather as the work of semiautonomous agencies that arise from extended mutualisms that build on themselves by endogenous selection from complex contingencies. Most contingencies, however, still serve in agonistic fashion to degrade system operation. This dualistic agonism between order-building agencies and entropic degradation unfortunately obscures the supporting but insufficient role of underlying universal physical laws. A new and more complete picture of causation in ecosystems appears to be tripartite, with physical constraints (laws) serving as constraining mediators between semiautonomous agencies and interfering contingencies. One is first inclined to represent the three–way relationship in linear fashion with agencies and entropy at the ends and lawful constraints in the middle. Further reflection, however, suggests that a better metaphor for the triumvirate of causalities is a Borromean unity, which is most commonly depicted by three rings securely interlocked in such a way that the removal of any one of them results in complete dissociation of the ensemble.

Addresses

[1] Department of Biology, University of Florida, Gainesville, USA
[2] University of Maryland Center for Environmental Science, Solomons, MD, USA

Corresponding author: Ulanowicz, Robert E (ulan@umces.edu)

Current Opinion in Systems Biology 2019, **13**:129–135

This review comes from a themed issue on **Systems ecology and evolution (2019)**

Edited by **Eors Szathmary** and **Ferenc Jordan**

For a complete overview see the Issue and the Editorial

Available online 7 January 2019

https://doi.org/10.1016/j.coisb.2018.12.006

Keywords

Agency, Apophasis, Autocatalysis, Borromean unity, Conditional entropy, Contingency, Law, Organization.

A determinate living world?

Ecology is the study of the relationships among populations of animals and their interactions with their environment. Patterned after earlier scientific disciplines, these connections were initially envisioned as mechanisms. The emphasis on mechanistic explanation of ecosystem behavior survives as perhaps the dominant approach [18,28], as if piling mechanism upon mechanism would ultimately lead to a full understanding of ecology. That prediction in ecology falls far short of what is expected from the 'hard' sciences does not dampen the 'physics envy' of reductionists [5].

Mechanical reductionists do not lack encouragement from physicists. Prominent Nobel laureates Murray Gell-Mann, Steven Weinberg, and David Gross have proclaimed, 'all causality originates from below and there is nothing 'down there' but the laws of physics' [13].

Problems with mechanical reductionism

But, desires by theoreticians are not always supported by empirical investigations. Witness the efforts of Sidney Brenner and associates, who during the 1960s attempted to map the elements of the simple genome of *Caenorhabditis elegans* to the phenotypic traits of the mature organism. In expressing his disappointment, Brenner recommended that "We have to discover the principles of organization, how lots of things are put together in the same place" [14]. Because organization bears upon ecology, renowned developmental biologist Guenther Stent was moved to reflect, "Consider the establishment of ecological communities upon colonization of islands or the growth of secondary forests. Both of these examples are regular phenomena … The regularity of these phenomena is obviously not the consequence of an ecological program encoded in the genome of the participating taxa."

There appear to be problems with the enterprise of mechanical reduction. Could it be that the force laws of physics are not capable of projecting their effects across the levels of the hierarchy to determine events at remote scales? Not that physics does not abound with examples of very precise predictions, but are such astounding successes to be universally expected? To address this question, one begins by scrutinizing the assumptions that undergird the power of the force laws. Such study reveals problems relating to history, dimensionality, logic, insufficiency, and contingency [33].

By way of somewhat surprising history, it is noted how Isaac Newton never presented his second law in its familiar form, “force equals mass times acceleration” (F = ma). Rather, it was Leonhard Euler who portrayed the world as a continuum. Newton’s statement, by comparison, remained discrete and irreversible [7]. Furthermore, Newton argued vociferously against Euler’s assumption because it effectively equates cause with effect.[3] It turns out that Newton’s rendition accords better with ecological relationships, most of which are irreversible processes, which explicitly involve time and thus elude representation by the fully time-reversible laws of physics.

As for dimensionality, symmetry in time means that time’s direction is not revealed by an event obeying the universal force laws. A video of such a phenomenon, similar to the elastic collision of two billiard balls, will give no clue as to whether it is being played forward or backward. Aemalie Noether [19] rigorously demonstrated that such reversibility implies conservation. That is, reversibility always allows one to define a potential function that is conserved (e.g. energy, momentum, etc.) and thus remains independent of time. Ecology rests more upon processes than upon conserved properties or objects. Processes are always irreversible and explicitly mark the passing of time. The discovery of irreversibility by engineers early in the 19th century posed a major challenge to classical reversible physics that endured for over 50 years. Late in the century, Ludwig von Boltzmann and Josiah Willard Gibbs, using an extremely simplistic model of noninteracting particles (a perfect gas) along with unrealistic assumptions (the Ergodic hypothesis) and random boundary conditions, were able to define a function that mimicked the uniform rise of entropy in real systems. The combination of simplistic particles acting according to reversible laws in the context of highly contrived boundary conditions was accepted as a conclusive reconciliation of reversible physics with the real world. Such an inference from a very narrow situation to establish a universal truth does not accord with either logic or the scientific method but has remained virtually unchallenged for almost a century and a half. The irreversible processes that comprise ecosystem dynamics, however, remain discordant with the time-independent nature of classical physics.

Perhaps even more problematic is the logic that undergirds the laws of physics, which over a century ago Whitehead and Russell [38] is rigorously demonstrated to be grounded in operations on homogeneous sets. Physics is all about homogeneous objects. Biology, by contrast, involves heterogeneity — in fact massive heterogeneity [8,9]. Heterogeneity is what Brenner hinted at when he mentioned ‘lots of things’. Now, laws cannot be applied without clearly specifying the contexts in which they operate — the ‘boundary value problem’, as it is called. Treating heterogeneous systems involves casting the laws separately for each distinguishable type of object and weaving the whole together with interlocking boundary conditions. As the number of types increases, the number of possible combinations among them grows hyperastronomically, and the combined boundary specifications become ‘unprestatable’ [15]. Elsasser et al. [8], for example, showed how the number of combinations among 75 distinguishable types exceeds the number of simple events could possibly have occurred anywhere over the whole duration of the known cosmos.

The impossibility of posing adequate boundary conditions is an epistemological difficulty. It might still be possible that the laws of physics determine all outcomes, even if a complete formulation of the problem cannot be achieved. The enormity of combinations among heterogeneous systems, however, challenges the ability of the laws to determine outcomes as well (an ontological deficiency). Massive heterogeneity almost always results in a very dense array of combinations of very small differences arbitrarily close to any chosen starting condition. Whence, infinitesimal noise at the level of the continuum assumption can send the system off onto a number of possible trajectories. All such alternative pathways will continue to satisfy the law, but the particular one that results remains indeterminate. That is, the laws are not violated, although they continue to constrain what can possibly occur, but beyond some degree of heterogeneity, they lose their power to determine particular outcomes. Be it noted, constraint is still a form of causality [11], albeit one less rigorous than strict determinism.

The mention of noise, even of infinitesimal magnitude, brings the role of contingency into the scenario. Here, the term ‘contingency’ is preferable to the word ‘chance’ because the latter is conventionally applied to events that are simple, directionless, indistinguishable (homogeneous), and repeatable — restrictions that circumscribe the application of standard statistical techniques. Such assumptions, however, delimit only a small fraction of the much wider spectrum of contingencies. Elsasser [8] argues that the number of compound events that can

[3] By taking the limit as $\Delta t \rightarrow 0$, the cause (F) and the effect (d^2x/dt^2) become simultaneous and therefore indistinguishable. As long as cause and effect are proximate and immediate, this creates no problem. For very short or long times and distances, however, this assumption causes difficulties — whence, the creation of the disciplines of quantum theory and relativity. The continuum assumption may also cause problems at intergalactic distances (e.g. ‘dark’ matter and energy).

arise is so enormous that a significant number will always appear unique over all space and time.

Obviously, radical unique events elude conventional statistical techniques. On the other side of blind chance appear other forms of arbitrary phenomena that occur under increasing degrees of constraint. Conditional probabilities, such as those exhibited by loaded dice, exhibit some degree of bias in directions that are influenced by surrounding events and conditions. Such bias can at times become dominant, giving rise to almost law-like propensities that yield the same outcome in a large preponderance of instances [21]. Hence, the real world presents an entire spectrum of contingencies, ranging from radical unique happenings to blind chance, to conditioned outcomes, and to propensities that approximate determinism.

The unanswered challenge

Returning to Carnot's phenomenological discovery of irreversibility,[4] it led to a universal physical law known as the second law of thermodynamics [3]. One of the many equivalent statements of the law says that in any unconstrained situation, the ability of a system to do work always decreases. Because work often appears as increased organization, the law also says that unconstrained systems inevitably undergo dissolution and decay, a class of phenomena known as increasing 'entropy'. For any real process, the entropy of the universe must increase.

As noted previously, von Boltzmann developed a formula for statistical mechanics that bore analogy to entropy. The identical formula was discovered independently by Claude Shannon to quantify the richness and variety of a statistical distribution. John von Neumann jokingly told Shannon he should call his formula the statistical 'entropy' because that is what Boltzmann called it. Furthermore, nobody truly understands entropy, so Shannon would always have an advantage in any argument. Shannon took von Neuman seriously, and the terminology passed into common use in both information theory and physics (In the latter, statistical mechanics became a 'sanitized' version of thermodynamics to replace the messier phenomenology of engineers).

There is a natural tendency in physical theory to focus on laws and to downplay the required conjugate boundary assumptions. Now, Boltzmann applied statistical mechanics to an ideal gas. By definition, the particles of an ideal gas are noninteracting. Under this restrictive boundary assumption, Boltzmann's index did indeed characterize the entropy of an ideal gas. But, is it more generally a faithful and full representation of the concept?

Phenomenological thermodynamics, for example, distinguishes between the total energy possessed by a system and the fraction thereof that can be converted into work. Conservation of energy is preserved by writing the total energy as the sum of useful energy and otherwise inaccessible energy as the sum,

$$U = G + TS, \tag{1}$$

where U denotes the total energy; G, the energy available to do work; T, the absolute temperature of the system; and S, the entropy of the system.[5]

It happens that G varies with the internal structure of the system and is zero for systems in which the particles do not interact (such as an ideal gas). Hence, it becomes unclear whether the Boltzmann index characterizes the total energy density (U/T) of a real system or its entropy S.

Ecology is defined, for the better part, as dealing with the interactions between distinct populations of living organisms, and the organization of an ecosystem is often equated to that of its interactions. To be more quantitative, let T_{ij} denote the trophic consumption by predator *j* upon prey *i*. A dot in place of a subscript will denote summation of the index over all members, for example, $T_{.j} = \sum_i T_{ij}$ and $T_{..} = \sum_{i,j} T_{ij}$. Under these definitions, the distribution of all trophic interactions according to Boltzmann and Shannon will appear as

$$H = -\sum_{i,j}\left(\frac{T_{ij}}{T_{..}}\right)log\left(\frac{T_{ij}}{T_{..}}\right) \tag{2}$$

A little algebra reveals that H can be decomposed into two nonnegative components, A and S, as

$$H = A + S \tag{3}$$

$$-\sum_{i,j}\left(\frac{T_{ij}}{T_{..}}\right)log\left(\frac{T_{ij}}{T_{..}}\right) = \sum_{i,j}\left(\frac{T_{ij}}{T_{..}}\right)log\left(\frac{T_{ij}T_{..}}{T_{i.}T_{.j}}\right) - \sum_{i,j}\left(\frac{T_{ij}}{T_{..}}\right)log\left(\frac{T_{ij}^2}{T_{i.}T_{.j}}\right), \tag{3a}$$

where A ($\geq$0) is called in information theory the 'average mutual information' and S ($\geq$0) is known as the 'conditional entropy' [17]. The upshot is that under realistic conditions in which the elements of a system do interact, the Shannon index incorporates *both* order (A) and disorder (S). It is misleading to refer to H simply as 'entropy' [35]. Rather, it represents an admixture of organized constraint (A) and

[4] In any conflict between empiricism and theory, the former always trumps the latter.

[5] G is the Gibbs free energy, appropriate under conditions of constant gas pressure. Helmholz defined a corresponding free energy, H, pertaining to constant-volume situations.

disorganized entropy (S). Although S carries the adjective 'conditional', that modifier is unnecessary because entropy is never unconditional, as demanded by the third law of thermodynamics [31]. Rutledge et al. [23] showed how S is a measure of the parallel pathways in a trophic network.

MacArthur [16] used H to quantify the diversity of flows in an ecosystem. Because flows are more inconvenient to measure than population sizes or densities, population densities eventually replaced flows in H, and the revised index became known as the system 'biodiversity'. It was intuited that biodiversity was correlated with system stability, which in turn was abetted by pathway redundancy. Odum and Odum [20] reasoned that if any supporting pathway in a system was disrupted by perturbation, compensatory resources could flow over unperturbed parallel pathways.

It was eventually discovered that biodiversity correlates rather poorly with trophic functional redundancy [34], the latter being quite accurately quantified by S [10].

It is quite important to recognize that S is apophatic in nature; that is, it represents something that does not exist — namely, constraints (which are quantified instead by A). The fact that entropy is an apophasis and not a positivist attribute explains why many have difficulty with the concept, envisioning entropy wrongly as a positivist notion, similar to energy or momentum. Entropy as apophasis also explains why no positivist model has been able to justify global efforts to conserve biodiversity. Apophases simply do not yield to positivist exegesis.

It might strike one at first as strange that nonexistence can be quantified, but such estimation is quite common, for example, 'The glass is half empty' — a reckoning of what is missing [32]. This simplistic example also illustrates that the apophatic can be quantified only with respect to what is real (the size of the glass). Whence, entropy can never be measured absolutely, but only with respect to some palpable standard (again, the third law of thermodynamics).

It remains to comment on the causal nature of entropy and the second law. Entropy does not push or constrain; it withdraws or disappears. That is, both agencies and laws operate either via some material entity or material-generated field. Entropy, however, is an apophasis in that its action is the result of the disappearance of such constraints. What results therefrom, more often than not, is viewed in a negative light as dissolution or decay, but alternatively, it can be regarded as opportunity. Although some authors view the second law as the final cause (sensu Aristotle) behind all evolution and development [24,27], its mode of action belies such interpretation: Nothing, acting by itself, can give rise only to nothing. As part of the larger causal scenario, however, it does play a significant role.

The drive behind order

Considerations of universal laws and increasing entropy have revealed no scenario whereby these two effects might increase system organization. Physical laws neutrally constrain, and the second law degrades. What, then, does determine, maintain, and advance the obvious order one observes in living systems? Here, it becomes tempting to point to the material genome as that which creates and sustains order. Material causality, however, is usually a passive actor in any dynamical narrative. Besides, the goal in ecology is to focus on processes, and more particularly upon configurations of processes, as that which determines development and evolution. Bateson [1] hints that the drive behind development lies in chains of irreversible processes that fold back upon themselves — feedback loops, which by their very nature defy closure (only material and efficient causes are allowed) and the Aristotelian prohibition against self-causality.

Among feedback configurations, one type deserves particular attention — autocatalysis. An autocatalytic cycle refers to one wherein every constituent process (link) supports and abets its succeeding member. Such circular mutual beneficence grows whenever any component process becomes more beneficial to its successor, and conversely, it declines whenever any benefit diminishes. Whenever memory resides in a system, the result is a ratcheting dynamic that will promote those changes that benefit the ensemble — a form of endogenous group selection [29,36]. Furthermore, because living entities always require energy and materials to survive, such selection will favor any change that augments the acquisition of these resources. Such contribution can be made by any member of the cycle, cumulatively resulting in ever greater flows of resources into the loop from all members, or what might be called 'centripetality'. None other than Russell [22] identified this dynamic as 'the drive behind all evolution'.[6] Competition thereby becomes secondary. It cannot occur at any level unless active mutual beneficence is already transpiring at the next lower level [29].

The key word in this picture is 'selection' — not the independent and anonymous external influence called natural selection, which acts mostly in a negative way to cull system members, but a noncognitive, endogenous agency that imparts advantage for the sake of the system to certain contingencies over and above others [25,29]. Unlike laws and entropy, autocatalytic selection actively determines outcomes in heterogeneous systems. The system doing the selection is the result of an historical series of 'frozen contingencies'. The selected variations require memory to persist, and one immediately calls to mind material forms, such as RNA/DNA, that supply

[6] Russell referred to the phenomenon as 'chemical imperialism', but the dynamic was clearly autocatalytic.

such memory to preserve changes. It is more likely, however, that the inherent stability of the autocatalytic matrix served as memory for the earliest living organic ensembles. These precursors of material genomes likely functioned to promote the transfer and control of energy and were exapted, along with their associated enzymatic and proteomic processes, to serve as durable memory [6]. Once having evolved their new role, they extirpated earlier, less enduring forms of memory.

To summarize, time-reversible laws constrain what is possible in development but cannot exert the symmetry-breaking selection necessary for progressive order. Increasing entropy is more likely to degrade system order, although it can open up opportunities for novel contingencies and heterogeneities. But, a growing heterogeneity of distinct types more than proportionately increases the probability that autocatalytic interactions will arise [12]. With autocatalysis, memory, and contingencies all in play, growth and development can commence: The members of an autocatalytic system are constantly exposed to arbitrary contingencies. Most such disturbances do not affect the system in any significant way. Some are harmful enough to degrade system performance, and survivors will adopt responses to redress perturbation. A small minority of contingencies will enhance mutual beneficence, and memory can then incorporate those changes into a more organized, autocatalytic system.

Nonrandom and indeterminate?

The scenario just sketched can be described as nonrandom, but indeterminate. For many, 'nonrandom and indeterminate' may at first sound like an impossible combination, but its feasibility can be illustrated by a metaphor used by physicist Wheeler [37] to portray the development of science in general.

Guests at a party decide to play a parlor game. One individual is sent out of the room, whereas the others choose a particular word to be guessed by that individual. Upon returning to the room, the subject questions members of the group in some loose rotation. Responses to the questions are limited to a simple binary 'yes' or 'no'. As soon as the questioner leaves the room, one guest suggests that the group *not* choose a word. Instead, the first respondent can answer 'yes' or 'no' on unfettered whim. Similarly, the second person is at liberty to make either reply, the only constraint being that his/her answer may not contradict the first reply. Similarly, the succeeding answers may not contravene any of the previous answers. The game ends when the subject asks, 'Is the word XXXXX?', and the only possible response is 'yes'. At any time, this game is nonrandom, being dependent on the previous history of questions and answers. The end result, however, cannot be predicted from the outset.

Connections among causalities

Wheeler's metaphor is a rich one and conveys even more than the union of nonrandomness and indeterminacy. The exercise is literally a conversation between the questioner, who is continually trying to narrow the range of possibilities, and the respondents, who mischievously attempt to maintain that range as wide as possible. The agonism between the aims of the two parties is reminiscent of a dialectic. This corresponds with the natural world wherein autocatalytic agency acts to select and narrow its cast of participants, whereas increasing entropy is always providing opportunities for new situations and participants [29]. The game progresses as constrained by its rules, which do not change, but allow for a near infinity of possible scenarios. By analogy, the universal and unchanging laws of physics modulate what can happen as systems develop in their manifold ways.

The correspondences between the parlor game and nature suggest an alternative to Aristotle's causal typology. Aristotle classified causalities in hierarchical fashion as material, efficient (mechanical), formal, and final. The Enlightenment consensus was that science should be limited to explanation in terms of only the first two categories. The three types of causalities identified here, however, span all four types. At first consideration, they seem to array themselves in linear manner, either horizontally or vertically (as in Figure 1).

At the top are the activities of autocatalytic agencies, which tend actively to organize processes into coordinated wholes. At the bottom are the results of increasing entropy, which tends to degrade and disorganize whatever agencies and nonliving forces have assembled. The tension reminds one of Heraclitus' vision of reality as the agonism between events that build up and those that tear down or of the complementarity [2] between the Eastern notions of Yin and Yan [39]. In between are the neutral universal laws that modulate the transactions between agency and entropy.

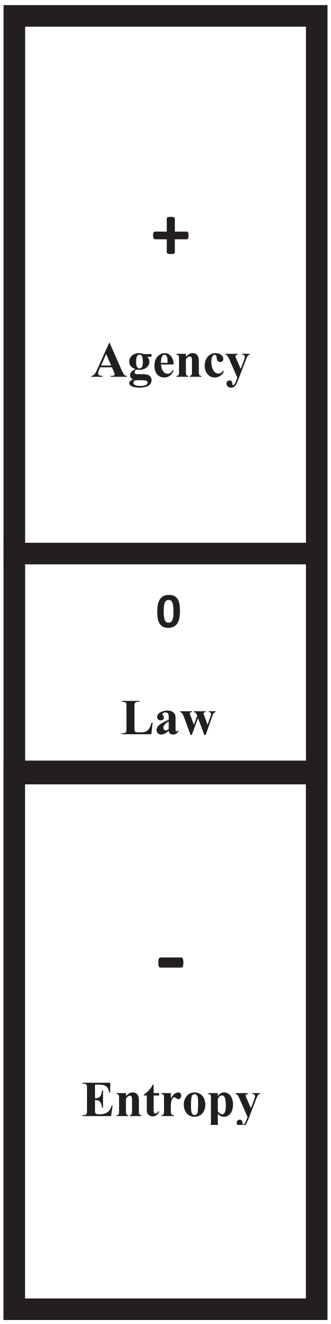
The conventional picture of development and evolution as arising over time due to only mechanical agency and blind chance appears as a minimalist caricature. In a quote attributed to Albert Einstein by poet Louis Zukofsky [40], "Everything should be as simple as it can be, but not simpler". Time-reversible laws and blind chance can lead only to decay and dissolution. Agency is required for progressive order.

In considering the relationships among agency, law, and entropy, the possibility presents itself that the overall structure of connections might be more complex than the linear one depicted in Figure 1. For example, many tripartite connections have been portrayed as Borromean in nature. The adjective 'Borromean' is taken from the coat of arms of the Borromean family of Northern

Italy. It consists of three rings tightly interlinked but in such a way that the removal of any one ring will cause the whole assembly to come apart (Figure 2).

Certainly, the absence of laws would mean that agency, should it appear, would not be confined enough to take on any particular direction, no matter how temporary. If entropy were to stop increasing, there would be no new contingencies from which autocatalysis could select those that improve its order.

Figure 1



Linear conception of the dialectic between active agency (+) and entropic disorganization (−), as mediated and modulated by universal physical laws (0).

Figure 2

Borromean rings as emblematic of the triadic interrelationship among agency, laws, and entropy. The excision of any one element leaves the remaining pair dissociated.

The lack of agency is perhaps the most questionable absence, seeing as how most can (and still do) conceive of an earlier physical world in which only laws and entropy were at play. It should be noted, however, that agency can be expressed by systems that are neither cognitive nor even living [29].

In fact, agency has been active since the very beginning of the physical universe. In the contemporary narrative, the universe began as a chaotic, incredibly dense mass of extremely high-energy photons — pure flux [4]. As this continuum began to expand, some of the photons came together (collided) to form pairs of closed-looped circulations of energy called hadrons, the initial matter and antimatter. For a while, collisions between matter and antimatter destroyed one another with equal frequencies that decreased as the universe expanded. Eventually, however, a very subtle (one in a billion) asymmetry (simple contingency) produced slightly more loops of matter than antimatter, so that a plurality of matter slowly accrued (selection). Further expansion gave rise to yet larger configurations of emerging materials and the appearance of weaker forces [26]. Gravity and larger entities ensued. Whence, the enduring materials one perceives today are actually the endpoints of dynamical configurations of processes, asymmetries, contingencies, and feedbacks of bygone eons. Agencies have been at work from the beginning, and without them matter, order and forces would not have emerged.

Not only are the three causalities bonded in Borromean fashion but also they likely coemerged that way from the beginning. It is necessary to keep in mind that many of the models that physics uses to draw universal conclusions, such as heat-death, are based on rarified systems of homogeneous tokens that interact only weakly, if at all [30]. Such systems, however, did not come into existence until the very later stages of the development of the cosmos. The universe came at us as a dense, strongly interacting and eventually heterogeneous system. The time has come to recognize a larger scope for development and evolution.

Conflict of interest statement

Nothing declared.

Acknowledgements

The author wishes to thank Malcolm Dean for continuing to explain to him the prevalence of Borromean unities in nature and society. Contribution #5548 of the University of Maryland Center for Environmental Science.

References

1. Bateson G: *Steps to an ecology of mind*. New York: Ballantine; 1972.
2. Brenner J: *Logic in reality*. Berlin: Springer Science & Business Media; 2008.
3. Carnot S: *Reflections on the motive power of heat. Trans. R. H. Thurston*. New York: ASME; 1824/1943.
4. Chaisson EJ: *Cosmic evolution: the rise of complexity in nature*. Cambridge, MA: Harvard University Press; 2001.
5. Cohen JE: **Irreproducible results and the breeding of pigs**. *Bioscience* 1976, **26**:391–394.
6. Deacon TW: **Reciprocal linkage between self-organizing processes is sufficient for self-reproduction and evolvability**. *Biol Theor* 2006, **1**:136–149.
7. Dellian E: **Die newtonische konstante**. *Philos Nat* 1985, **22**: 400–405.
8. Elsasser WM: **Acausal phenomena in physics and biology: a case for reconstruction**. *Am Sci* 1969, **57**:502–516.
9. Elsasser WM: **A form of logic suited for biology?**. In Rosen Robert. *Progress in theoretical biology*, vol. 6. New York: Academic Press; 1981:23–62.
10. Farnsworth KD, Albantakis L, Caruso T: **Unifying concepts of biological function from molecules to ecosystems**. *Oikos* 2017, **126**:1367–1376.
11. Juarrero A: **Causality as constraint**. In *Evolutionary systems*. Dordrecht: Springer; 1998:233–242.
12. Kauffman SA: **Autocatalytic sets of proteins**. *J Theor Biol* 1986, **119**:1–24.
13. Kauffman SA: *Reinventing the sacred: a view of science, reason and religion*. New York: Basic Books; 2008.
14. Lewin R: **Why is development so illogical?** *Science* 1984, **224**: 1327–1329.
15. Longo G, Montévil M, Kauffman SA: *No entailing laws, but enablement in the evolution of the biosphere*. 2012. arXiv: 1201.2069 [q-bio.OT].
16. MacArthur RH: **Fluctuations of animal populations and a measure of community stability**. *Ecology* 1955, **36**: 533–536.
17. McAEliece RJ: *The theory of information and coding*. Reading, Massachusetts: Addison-Weseley; 1977.
18. Nakajima T: **Ecological mechanisms of evolution by natural selection: causal processes generating density-and-frequency dependent fitness**. *J Theor Biol* 1998, **190**:313–331.
19. Noether A. In *Gesammelte Abhandlungen*. Edited by Jaconson Nathan, New York: Springer Verlag; 1983.
20. Odum EP, Odum HT: *Fundamentals of ecology*. Philadelphia: XV. B. Saunders Co; 1953.
21. Popper KR: *A world of propensities*. Bristol: Thoemmes; 1990.
22. Russell B: *An outline of philosophy*. Cleveland: Meridian Books; 1960.
23. Rutledge RW, Basore BL, Mulholland RJ: **Ecological stability: an information theory viewpoint**. *J Theor Biol* 1976, **57**: 355–371.
24. Salthe SN: **The natural philosophy of entropy**. *Seed* 2002, **2**.
25. Sharov AA: **Evolution of natural agents: preservation, advance, and emergence of functional information**. *Biosemiotics* 2016, **9**:103–120.
26. Smolin L: *The life of the cosmos*. Oxford: Oxford University Press; 1999.
27. Swenson R: **Emergent attractors and the law of maximum entropy production: foundations to a theory of general evolution**. *Syst Res* 1989, **6**:187–197.
28. Todd J, Josephson B: **Living machines: theoretical foundations & design precepts**. *Annal Earth* 1994, **12**:16–24.
29. Ulanowicz RE: *A third window: natural life beyond Newton and Darwin*. West Conshohocken, Pennsylvania: Templeton Foundation Press; 2009a.
30. Ulanowicz RE: **Increasing entropy: heat death or perpetual harmonies?** *Design Nat Ecodyn* 2009b, **4**:1–14.
31. Ulanowicz RE: **Towards quantifying a wider reality: Shannon exonerata**. *Information* 2011, **2**:624–634.
32. Ulanowicz RE: **Reckoning the nonexistent: putting the science right**. *Ecol Model* 2014, **293**:22–30.
33. Ulanowicz RE: **Process ecology: philosophy passes into praxis**. *Process Stud* 2016, **45**:72–95.
34. Ulanowicz RE: **Biodiversity, functional redundancy and system stability: subtle connections**. *J Roy Soc Interface* 2018, **15**:20180367.
35. Ulanowicz RE, Goerner SJ, Lietaer B, Gomez R: **Quantifying sustainability: resilience, efficiency and the return of information theory**. *Ecol Complex* 2009, **6**:27–36.
36. Wicken JS, Ulanowicz RE: **On quantifying hierarchical connections in ecology**. *J Soc Biol Struct* 1988, **11**:369–377.
37. Wheeler JA: **Beyond the black hole**. In *Some strangeness in the proportion*. Edited by Woolf H, Reading, Pennsylvania: Addison-Wesley; 1980:341–375.
38. Whitehead AN, Russell B: *Principia mathematica*. Cambridge: Cambridge University Press; 1913.
39. Xu Z, Cheng G, Ulanowicz RE, Song X, Deng X, Zhong F: **The common developmental road: tensions among centripetal and centrifugal dynamics**. *Natl Sci Rev* 2018, **5**:417–426, https://doi.org/10.1093/nsr/nwx033/3101042.
40. Zukofsky L: *Poetry in a modern age*. 1950.