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Widening the Third Window

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Abstract The respondent agrees with William Grassie that many windows on nature are possible; that emphasis must remain on the generation of order; that ‘‘chance’’ would better be recast as ‘‘contingency’’; and that the ecological metaphysic has wide implications for a ‘‘politics of nature’’. He accepts the challenge by Pedro Sotolongo to extend his metaphysic into the realm of pan-semiotics and agrees that an ecological perspective offers the best hope for solving the world’s inequities. He replies to Stanley Salthe that he now agrees that the second law of thermodynamics is the overarching law of nature, but only when the duality inherent in of the concept of entropy is widely recognized. The respondent is enthusiastic over Jeffrey Lockwood’s extrapolation of process ecology to include the concept of ‘‘species’’ and over John Haught’s description of how the construct paves the way for a ‘‘theology of evolution’’ by recasting evolution as an unfolding ‘‘drama’’.

Keywords Causality, Ecological metaphysics, Evolution, Semiosis, Thermodynamics, Theology, Species concept

1 Eliciting Manifold Reactions

Any thesis that addresses the foundations upon which the natural sciences frame reality is likely to elicit a plurality of reactions from different directions. The foregoing five reviews of my essay, A Third Window (3W), display three distinct attitudes. The first of these (Grassie) adopts a posture of inquiry either to clarify points or to elicit my intentions. The two essays that follow pose constructive

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challenges to my positions. Sotolongo presses me to take a broader view of semiotics than I had maintained while writing my text, whereas Salthe questions my dualistic view of natural dynamics in favor of the encompassing monism he constructed upon the second law of thermodynamics. The final two commentators use the ecological metaphysic elaborated in my book as a platform from which to launch their own extrapolations. Lockwood, a long-time process thinker, provides a hierarchical link missing from my narrative when he argues that species are better defined as collections of processes. Finally, Haught makes a transcendental extrapolation by suggesting that the ecological metaphysic provides for a fecund theology of evolution by casting the development of the cosmos as a drama.
I begin by responding to Grassie's four important queries:

2 Many Windows

William Grassie, through his founding of Metanexus, is well-known for his broad perspective on the human enterprise. It is, therefore, both humbling and enriching to consider questions he poses about how the ecological metaphysic might help us make sense out of the emerging science of complexity.

In his first section Grassie observes that (a) in spite of my views on the granularity of nature, significant universalities nevertheless persist, and (b) (as suggested by the excellent quote from Goodall) manifold windows exist thru which nature can be fruitfully examined.

I will not refute either contention, for there indeed exist conditions under which either or both statements are accurate. Much depends, however, as to where on the hierarchical scale one chooses to observe the world. Of particular interest is the difficult-to-measure scale of complexity—how finely one wishes to distinguish categories.

It is a simple truism that universal laws must be stated in terms of universal variables. To see, for example, the universality of Newton's second law requires that one ignore all differences between objects, save for the universal property called ''mass''. Under such a broad-brush abstraction, Newton's second law remains inviolate insofar as it pertains to the realm of biology. There it is a universal[1] and will remain so. The same goes for the other three force laws of physics.
The incredible strength of abstraction for the largely homogeneous realm of physics becomes a major weakness when applied to the domain of biology—that arena of inquiry where focus is directed towards what Bateson called ''the difference that makes a difference''. Not to put too fine a point on it, in biology the attitude of ''physicalism''—that everything is determined by the universal laws of physics constitutes an egregious minimalism.

To see why the laws of physics do not determine particularities, it becomes necessary to appreciate that there are two elements necessary for the full statement of a problem. A physical scenario is traditionally stated in terms of a field over which phenomena are rigidly constrained by law and a set of contingent particulars

1 Relativistic effects at the scales of biology appear negligible.

that stipulate conditions at the boundaries of the field and/or at the initial time. It is essential to the definition of any universal law that the boundary statement remains totally arbitrary, for if some subset of boundary conditions were disallowed, the law no longer would be universal. Whence, any slice of reality portrays necessity bounded by contingency.

For the most part, boundary conditions are implicitly assumed to be set by the individual who poses the problem. Once the contingencies are set, the laws then constrain what can transpire over the field. Change the boundary contingencies and the variables within the field change accordingly. The emphasis heretofore has been on how the laws ‘‘determine’’ the values in the interior of the field, when in fact those laws are passively reacting to the boundary ‘‘drivers’’.[2] The laws of physics are symmetric with respect to time and so cannot of themselves produce any novelty. Any real change must enter via asymmetry in the boundary drivers, which necessarily are contingent.

A word about ‘‘contingency’’: The central notion is that of something that is unforeseen. It is something that is completely arbitrary. It does not follow (neither is it ruled out) that a contingency be a matter of blind chance. In fact, the more common assumption has been that contingency is the result of human intention (values set by the person posing the problem).[3] Whence, contingency applies to a range of phenomena from blind chance to Bayesian conditional chance (Depew 2011) to Popper’s (1990) propensities (effects that almost always follow upon certain conditions) on up to intentional determinism.

In dealing with particulars, therefore, it becomes necessary to shift emphasis away from universals and towards contingencies, for it is only the asymmetries in boundary contingencies that can give rise to true change. Furthermore, a contingency at one point of a field can be propagated by lawful action across the field to another point on the boundary, where it may in turn serve as a contingent driver to an adjacent field. It is not difficult to conceive of situations wherein the effects of a contingency are fed back upon themselves in a positive way so that the original contingency is either sustained or abetted in autocatalytic fashion. Such configurations of contingencies then appear as persistent regularities. These regularities are mediated and maintained by universal laws, but their inception lay not with those laws, but rather with an evolutionary constellation of contingencies.

Do universals exist? To be sure, and they are essential to the maintenance of regularities. But as soon as one focuses upon any particular regularity (as is the interest in biology), the most important elements to any explanation become the historical contingencies, not the accessory universals.[4]

2 Systems engineers often talk about ‘‘driving’’ a model via temporally varying boundary circumstances.

3 In keeping with the Newtonian exclusion of the observer, the boundary problem has been marginalized and the focus of causality has been fixed upon the constraint of law.

4 Many biologists will object that the process approach ignores the material universality of DNA in life processes. While DNA/RNA does appear to be common to all life on earth, it is questionable whether it was always ubiquitous. Deacon (2006), for example, argues how molecular genomes could have evolved for dynamical reasons out of pre-existing configurations of early biochemical processes and became universal only after displacing earlier, less effective forms of memory.

Do many windows on reality exist? They most certainly do—in fact, as many as there are individuals engaged in describing nature. The title of my book has been criticized by others who have suggested various paradigms outside of those associated with Newton and Darwin. For the sake of expository clarity, however, I have borrowed a page from the physicist and intentionally blurred most distinctions other than to recognize those two encompassing theories in order to emphasize what is new and potentially useful about process ecology.

2.1 The Second Law

Regarding the relationship between the second law and my putative dynamics, Grassie writes, ‘‘…he [Ulanowicz] understands patterns and forms in nature as the result of ‘agonistic tendencies’ and ‘dissipative losses’’’. That statement does not convey what I had intended on pp. 116–118 of 3W. Rather, I was following Heraclitus by inferring that natural forms are the outcomes of two agonistic tendencies—the first being a drive towards building up order and the second, the contrasting decay resulting from dissipative processes. I never entertained any thought of emphasizing the latter over the former—quite the opposite.

I devoted pp. 60–80 of 3W to the heuristics of how indirect mutualism or autocatalysis might serve as the primary drive behind the continual appearance of order. I enumerated eight attributes of autocatalytic dynamics that differentiate them from conventional mechanical behavior. I argued further how the centripetality elicited by autocatalysis imparts ontological priority to mutuality over the competition that is central to contemporary evolutionary narratives (p. 73). I intentionally downplayed the neologism ‘‘ascendency’’ that I had used earlier to refer to the process counterpart of what Erwin Schro¨dinger had called ‘‘negentropy’’.

The putative drive towards higher ascendency reinterprets the neglected half of Darwin’s narrative. Following Malthus, Darwin posited the profuse creation of forms over and against an eliminative selection that pruned from among them. Under the rubric of ‘‘natural selection’’ the Neo-Darwinian narrative concentrates almost entirely on the latter tendency and blithely passes over the generative aspects that arise out of autocatalytic dynamics. A significant motivation for writing 3W was to restore balance to the Darwinian scenario.

Chaisson (2001) outlined a tendency of evolutionary systems to increase in their throughput of energy per unit matter—a direction that accords well with increasing ascendency, and one that was prefigured in an earlier essay I wrote with Bruce Hannon (Ulanowicz and Hannon 1987). So it was perplexing when I learned that I had not communicated to Grassie the emphasis I place on the origins of order in living systems. My story is one of increasing ascendency in constant opposition to increasing entropy.

My disappointment notwithstanding, I should immediately admit that the agonism could have been portrayed better and in more didactic terms. Since the publication of 3W, I have formulated an argument against the monist claim that heat death is the sole eschatological end of the cosmos (Ulanowicz 2009a). Toward this end I cited how Boltzmann and Gibbs portrayed the second law as acting on a highly artificial system of rarefied, homogeneous, non-interacting tokens (an ‘‘ideal gas''). Under such highly restrictive conditions, increasing entropy can only lead to full dissipation, or ''heat death''. Whence, many academics have rushed to extrapolate the implications of the Boltzmann model into what Haught has described as ''a cosmology of pessimism''.

Rather, it happens that heat death is no longer inevitable, once one allows the elements of a system to interact with one another. Significant interaction between system elements gives rise to a second possible endpoint that is characterized by equilibrium configurations of closed, equiponderant interactions. Being at equilibrium, such structures are capable of persisting in the absence of further inputs of material or energy. Real dissipative structures, such as living systems, are positioned between these hypothetical limits of total disorder (heat death) and what I have called ''perpetual harmonies'' (usually falling closer to the former).

The question naturally arises whether anything resembling perpetual harmonies exists, and if so, how did such forms come about? Addressing the second question first, we ask what becomes of a dissipative system as its resources are slowly removed? Does it degrade entirely into heat, or does some persistent residual emerge? The putative history of the expanding cosmos suggests that perpetual harmonies have indeed arisen (Chaisson 2001). We call them quiescent matter.

During the early expansion of the universe energy density was falling rapidly. A point was reached where miasma of subatomic particles precipitated several stable forms, such as hydrogen gas or the helium atom. All of the asymmetries in energy and radical matter eventually left behind residual heat that is still perceptible as a 3K background radiation. The accretion of heavier atoms, many of them capable of entering into stable combinations, then took place among the nuclear reactions of stars. In the absence of strong perturbations, many of these stable forms involve of the motion of subatomic particles that can persist indefinitely without any additional inputs.

And so my response to Grassie's concerns about the inevitabilities of the second law resembles an observation that Eric Chaisson (whom Grassie cites) arrived at independently: The increase of entropy in complex systems reveals two aspects (Ulanowicz 2009a). The more obvious tendency pulls everything towards heat death. The less-apparent side provides opportunities for mutualistic agencies to arise and combine to create new ordered forms.[5]

2.2 Chance and Necessity

One discerns in Grassie's comments a certain disdain for the notion of ''chance'' and ''random'', as though he would rather banish these term from the evolutionary vocabulary. I share his concern insofar as every mention of chance seems intended to disqualify any hint of direction. One needs to keep in mind that the theory of probability focuses upon chance that is simple, homogeneous, repeatable and isotropic, i.e., ''blind''. But not all occurrences of chance meet these criteria.

5 Perpetual harmonies inevitably remind one of Thielhard de Chardin's Omega Point. Not that it is easy to imagine what could possibly be the harmonious outcome of this chaotic dissipative structure called human society, but more importantly, that, as I mentioned in the last sentence of 3W, pessimism is no longer the only attitude possible.

On p. 43 of 3W I suggested the notion of ‘‘complex chance’’ that is a composite of simple events. Such chance can exhibit local directionality and can be completely unique (novel) in the history of the universe, thereby eluding treatment by statistical methods.

Approaching the aleatoric from the opposite direction, Popper (1990) argues that deterministic forces be replaced by ‘‘propensities’’—tendencies that give rise most of the time to a particular outcome. The outcome is not unique, however, in that a variety of other outcomes can and, on occasion, do occur.

Some reflection should reveal that arbitrary events span a virtual continuum from pure, blind chance to absolute determinism (necessity). Furthermore, it would appear that tokens from the entire gamut at various times play a role in the evolutionary process. Therefore, lumping all arbitrary events under the rubric of ‘‘chance’’ and ‘‘randomness’’ becomes highly misleading. Encouraged by Grassie’s challenge, I am now inclined to favor the less baggage-laden term ‘‘contingency’’ to designate anything touching upon the aleotoric.

Such adjustment of terminology notwithstanding, one still cannot ignore the efficacy of statistical methods as a methodological tool in biology. Under its restricted conditions, it works amazingly well, so that I am not ready to dismiss the notion of blind chance as merely deterministic events to which we cannot assign exact causes.

Overall, my attitude toward chance and statistics in a way parallels and complements my position regarding law: Law is certainly instrumental in all natural phenomena; but, as I argued above, it is only one part of the story. Both law and contingency are at work in any real situation, and neither is present without the other. Chance becomes circumscribed for almost the same reasons that law remains insufficient—entities are heterogeneous and they interact significantly with one another. Palpable interactions between system elements and the hyper-astronomical number of combinatoric possibilities among chance events preclude the application of existing statistical methods to most situations involving the aleotoric.
Rather than banishing the concepts of chance and randomness, I would prefer to point out their limited roles in affecting heterogeneous life. Furthermore, to avoid false absolutes, I would urge the adoption of ‘‘contingency’’ in reference to all nondeterministic systems. I see in all possible manifestations of chance an irresolvable proposition: Is chance a proper ontological category or an epistemological illusion? Are quantum phenomena manifestations of radical chance, as promulgated by the Copenhagen Convention, or of some ‘‘implicate order’’, as Bohm suggests? The resolution lies irretrievably behind what in 3W I called the ‘‘epistemological veil’’ (Ulanowicz 1999).

If some should find this veil frustrating, they would do well to consider that to speak of nature entirely in terms of either determinate law or meaningless chance, is simply otiose. The full statement of any problem always requires both law and contingency. In purely physical systems it is often easy to disregard the contingency and pretend that law sufficies. With life, however, one simply cannot avoid the necessity for contingency. I heartily agree with Grassie’s citation of Whitehead and Teilhard’s characterization of beauty as the interplay between order and chaos.

2.3 Process as Politics

In the wake of the scientific revolution, social behavior has become highly informed by how science regards nature. The emphasis in science upon the material has influenced movements as disparate as the science of economics or the secularization of European nations. It seems to follow that any shift away from objects and law and towards configurations of processes might have equally far-reaching consequences on socio/political domains. For me, focusing upon relationships in lieu of objects could go a long way toward restoring humanity to science. Gone would be the temptation to regard an individual a merely a large collection of molecules. History, both personal and social, could no longer be considered epiphenomenal, but instead should become an integral part of scientific discourse.

Accepting the complex nature of causality should change how blame is assessed in law and ethics. For example, the search for the causes of the Challenger disaster would not have been limited to mechanical defects. Rather it would have been expanded to consider whether cutbacks to the space program might have led NASA to de-emphasize reliability and redundancy.

A transactional image of natural dynamics would represent the return to a dualist philosophy, albeit not in the sense of Descartes. Reality would instead appear as a tradeoff between the building and dissolution of order, and the necessity of both would become paramount. A view of nature arising out of a balance would put the lie to monist ideologies that beset contemporary politics and economics. For example, the current sine-qua-non of modern economics is market efficiency. In this last decade we have witnessed how an economy driven to high efficiency becomes vulnerable to collapse (Lietaer et al. 2009). Currently, the US political stage is set by two parties, each of which pursues its own monist ideology to the strong exclusion of the other—a surefire formula for disaster! Making clear how systems in nature that pursue a monist course fail to endure might return a degree of sanity to the political process.

A process worldview could shift attention in science away from its preoccupation with the microscopic (e.g., molecular biology) and awaken investigators to the causal roles of higher-level processes. For example, appreciating how genes do not determine everything in development and metabolism should direct more research effort towards mid-level enzymatic and proteomic processes. In cancer research less attention would be paid to ‘‘oncogenes’’ and more to the dynamics of the human immune system. The origin of all causality would no longer be subatomic. ‘‘Physics envy’’ would evaporate, as the public comes to understand why large scale ecological and social systems require indeterminacy to persist. The derogative ‘‘soft’’ would be dropped from the description of the biological and social sciences; the chasm separating the sciences from the humanities would diminish considerably.

Perhaps the discipline most affected by process ecology is evolutionary theory, where many theorists remain steadfastly opposed to any evolution of the theory itself. Darwin (perhaps unintentionally) described evolution as a process, not a law. Those responsible for his legacy, however, recast his story in the mold of law-actson-matter. Whereas Darwin was interested in the interaction between generation and elimination, subsequent renditions have focused almost exclusively upon the eliminative aspect called ‘‘natural selection’’. Regarding evolution explicitly as process would restore legitimacy to the facultative selection that always accompanies growth. Competition would no longer be the primary driver of evolution, because all competition requires an antecedent mutuality. Through the same lens, cooperation and altruism would be regarded as primary in their own right, rather than as exceptions that must be interpreted in terms of competition. The pursuant ethical ramifications could be profound—as radical as the differences between the Social Darwinism espoused by Thomas Huxley and the consequences of Trinitarian love, as depicted by Augustine of Hippo and Giovanni di Fidenza.

This last example keys one to the ongoing dialog between science and religion. In 3W I argued as how the Enlightenment metaphysic arose out of the need to insulate an inchoate but burgeoning young science from clerical interference. Insulation morphed into conflict as any number of issues arose ostensibly to separate matters of belief from a clockwork image of law-acting-on-matter. By contrast, it is difficult to imagine such trenchant conflicts arising between process philosophy and religious belief, which is not to say that process ecology in any way verifies transcendental belief. It simply obviates or mitigates conundrums, such as free will, Divine intervention, or theodicy (Ulanowicz 2004).

The list of consequences from the process viewpoint hardly ends here. There exists virtually no realm of human endeavor that would not be affected in some measure by paying more attention to processes over objects.

3 Looking Through the Third Window

Pedro Sotolongo begins his remarks with some very personal observations, and I will accordingly follow suit. In reading various works by Sotolongo, I am continually struck by the concordance between our fundamental directions, and I find such consonance to be strong reason for hope. It happens that Pedro and I were raised under competing ideologies (he Communist, I Catholic) and were trained in disparate fields (he, in philosophy/sociology; I, in engineering/ecology). Yet, without either betraying his respective legacy, we have been able to embrace those commonalities upon which we believe a just future for humanity can be sustained.

Of course, philosophical dialogue should not dwell too long on commonalities, but is meant to explore instead areas of divergence in the hope that resolution of those points will lead to mutual illumination. It is in such collegial spirit that Pedro challenges my reluctance in 3W to embrace what has been termed ‘‘pan-semiosis’’—the idea that information, sign and meaning pertain as well to the abiotic world.

3.1 Dynamics and Semiosis

I come out of a scientific tradition that emphasizes dynamics—more particularly out of thermodynamics—the phenomenology of transformations of matter under the aegis of energy. I have followed with great interest attempts to extend dynamics into the realms of the living (Prigogine 1978) and even the conscious (e.g., Juarrero 1999) realm. My interest in the phenomenology of living systems (ecosystems in particular) has brought me into contact with yet another approach to the phenomenon of life—semiosis, or the study of information, signs and meaning. I confess I was initially very skeptical of semiosis as being ‘‘too anthropogenic’’—an attitude from which I was dissuaded by some of Jesper Hoffmeyer’s (2008) intriguing examples of insect behavior. Still, at the time I was writing 3W I was unwilling to embrace the idea that semiosis pertains as well to the abiotic world. And so I made the distinction cited by Sotolongo, ‘‘I [saw] the transition from the prevalence of dynamism over semiosis to the [dominance] of semiosis over dynamism, [as occurring] when the combinatorics of future possibilities overwhelms the capabilities of universal laws to determine outcomes.’’

In this volume Pedro devotes most of his essay to the proposition that dynamics and semiosis are universally complementary (in analogy to the sense in physics that subatomic entities can be regarded alternatively as either particles or waves). Not only do conventional dynamics remain at work in cognitive systems, but he maintains as well that semiosis has been operative in the cosmos prior to the origin of life on earth. In heuristic fashion Sotolongo argues that atomic combinations engage in ‘‘sensing’’ their molecular environment for propitious conditions to combine with other elements.

Through work I have done in the wake of 3W, I am now more open to the pan-semiotic perspective. I an article recently-published in Information, I argued that the calculus of information theory, despite its origins in the cognitive field of communications theory, can be applied as well to quantify simple physical constraint (Ulanowicz 2011). I reasoned further that the third law of thermodynamics requires information, like its complement, entropy, always to be used in relative and never in absolute fashion. It is only by recognizing the relational nature of information that meaning can be usefully addressed. To buttress this proposition, I provided a very simple numerical exercise, which I now believe is relevant to Sotolongo’s heuristics.

The example consisted of three random strings of 200 digits:

Sequence A: 42607951361038986072061245134123237671363847519601557824849686201007746224524209371591449046940565604803389860720612451341232376713638475196015578248496862010077462245242093715914490469405656048033898

Sequence B: 036177464392420937159144904694056560480338986072061245134123237671363847519601557824849686201007746224524209371591449046940565604803389860720612451341232376713638475196015578248496862010077462245242 09

Sequence C: 014756238437896947517431023803181854538489052364732259109064941737355041602101768532630067046072424709718969475174310238031818545384890523647322591090649417377950411021017685326300670460724247097089 69

I will spare the reader any equations, suffice it to report that the metric of comparison that I used is called ‘‘mutual information’’—a Bayesian (conditional) component of Shannon’s more famous (and non-conditional) measure of information. I first used this metric to test whether each digit in a string was related in any way to its neighbor. Each string, when considered alone, appeared to be completely random. I then applied the same metric to compare digits in the corresponding positions of each string. The relationships between corresponding pairs in A and B and between those in B and C again proved to be random. The measure between positions in A and C, however, turned out to be very high and approached the maximum possible for two strings of this particular length. This was because each digit in C is an arbitrary transformation of its correspondent in A, save for a handful of ‘‘mistakes’’.

Superficially, these comparisons can be regarded as routine exercises in coding/decoding, but they point to something deeper: If, instead of digits, I had used symbols for codons in a genome (A,C,T,G) or monomers in a protein (Gly, Ala, Leu, Trp, etc.), the exercise would take on biological implications. For example, when applied to proteomics, sequence A could represent the order of amino acids on the outer surface of an antibody in the plasma of an organism, while B and C could describe corresponding patterns on the surfaces of microbes present in the same fluid. While B appears to bear no relationship to A, C would match A in almost ‘‘hand-in-glove’’ fashion.

From the perspective of immunology, the pattern in microbe C would provide ultimate meaning to antibody A. The match would signify the end towards which A was created by the immune system and would initiate a highly directed action on the part of A (to eliminate the microbe). The relevance to Sotologo’s argument is striking and straightforward. The strings of amino acids can be considered in physical abstraction from the living organisms of which they are part. The matching is the act of interpretation of the environment, or in Sotolongo’s words, it is what allows the antibody ‘‘to recognize its molecular surrounding environment’’ and become linked to it in a meaningful way. The example suggests that semiosis in the abiotic atomic realm is eminently plausible—a proposition that many followers of Peirce have long maintained.

3.2 Indeterminacy Redux

Considering the extension of semiotics downwards into the molecular realm has prompted me to revisit my criterion for the threshold of semiosis—namely, when the combinatorics of future possibilities overwhelms the capabilities of universal laws to determine outcomes. In hindsight it is apparent that I had formulated this criterion in terms of the present cosmos, rather than in the framework of an evolving universe. As I speculated in 3W, evolution, in the larger sense suggests that the universal laws of nature evolved along with the cosmos itself. That is, it is likely that the four force laws of physics initiated as contingencies within inchoate processes that later ‘‘precipitated’’ into universal, ubiquitous and unchanging ‘‘laws’’. The adiabatic expansion of the cosmos suggests that the strong nuclear force was likely the first to emerge, followed in sequence by the weak nuclear force, then by columbic attraction and finally[6] by gravitation.

6 The conundrum over ‘‘dark’’ energy and matter prompts the speculation that one or more additional forces may be at work in the cosmos and remain to be formulated in terms of new law.

Under this evolutionary scenario, the boundary for the onset of semiosis has not remained fixed, but rather was a moving threshold. Early in the cosmos, laws were very few and indistinct, so that the combinatorics among only a few differentiated forms would have sufficed to overwhelm the ability of those sparse extant laws to determine events. The upshot is that semiotic-like behaviors likely have been possible since the very inception of the universe.

These thoughts on the moving threshold of semiosis prompt me to revisit and elaborate what I wrote above about the insufficiency of universal laws to determine events. We recall that contingencies can span the gamut from conventional ‘‘blind chance’’ to conditionally probable (Bayesian) events, to the ordering propensities of Popper (1990), and finally to the intentions of a cognitive agent. In Chap. 4 of 3W, I argue how autocatalysis can select among and maintain those component processes that contribute best to the overall scenario of autocatalysis. The same reasoning can be applied to circular configurations of contingent events that are linked with each other via deterministic laws. In this scenario the evolution of events is being driven by the contingencies, not by the connecting laws, which by comparison play the relatively passive role of guiding conduits.

This radical perspective is nicely illustrated by a metaphor suggested by the eminent physicist Wheeler (1980). Wheeler was highly sensitive to the non-classical nature of particle physics and suggested that the constructivist character of his discipline, and by inference of science in general, might resemble a parlor game: As Wheeler spins it (3W, p. 14), a number of guests are invited to a dinner party. Dinner is late, and so the hostess bids the company to entertain themselves with a game. They elect to play the game ‘‘20 Questions’’ in which the object is to guess words. That is, one individual is sent out of the room while those remaining choose a particular word. It is explained to the delegated person that upon returning, he/she will pose a question to each of the group in turn and these questions will be answered with a simple ‘‘yes’’ or ‘‘no’’ until a questioner guesses the word. After the chosen player leaves the room, one of the guests suggests that the group not choose a word. Rather, when the subject returns and poses the first question, the initial respondent is completely free to answer ‘‘yes’’ or ‘‘no’’ on unfettered whim. Similarly, the second person is at liberty to make either reply. The only condition upon the second person is that his/her response may not contradict the first reply. The restriction upon the third respondent is that that individual’s reply must not be dissonant with either of the first two answers, and so forth. The game ends when the subject asks, ‘‘Is the word XXXXX?’’ and the only response coherent with the previous replies is ‘‘yes’’.

Wheeler’s metaphor speaks cogently to a constructivist science, but we now see how it applies as well to the very nature of evolution itself: The rules of the game correspond to the laws of nature. Presuming the game is played fairly, the rules are not violated, but their role is relatively passive—they are simply to guide activity. In no true sense do they actively determine the particular endpoint. That outcome is the result of a conversation between contingencies that originate from the questioner and the respondent. The questioner is attempting to narrow the range of possibilities and close in on the word. By contrast, the respondents are trying to keep the range of possibilities as wide as feasible for as long as possible. The rules did not determine the endpoint. It arose as the historical result of a series of contingencies, progressing from virtually blind chance to determinism over the course of the game.

This depiction of the transactional nature of evolution is the very one I attempted to portray in A Third Window. The dynamics of nature resemble a Heraclitian dialectic between (a) configurations of processes (such as autocatalytic cycles) that generate progressive constraints to activity over and against (b) the ubiquitous tendency of the second law to degrade order. Universal laws are quite necessary and play a significant role, but it is historical contingencies that actually lead the ‘‘drama’’, as Haught (see below) would call it. It is highly misleading to portray evolution in clockwork fashion as ‘‘matter moving according law’’ (Ayala 2009). Rather, as Sotolongo suggests, reality appears in response to signs and their interpretations; and the metaphor suggested by such a pre-eminent physicist as Wheeler infers that semiotic activity penetrates deep into the history and fabric of the universe.

3.3 Normative Consequences

Pedro concludes his remarks by citing some critical problems that challenge global society and by indicating how complexity theory might help the world to avoid disaster. Since the publication of 3W, I too have addressed the implications of the ecological metaphysic for economic theory (Ulanowicz et al. 2009; Lietaer et al. 2009). The keystone of my considerations has been the dynamics of autocatalysis, or more generally, indirect mutualism. In particular, I emphasize the phenomenon of ‘‘centripetality’’ that is engendered by such configurations—the tendency of self-reinforcing processes to bring ever increasing resources into their orbit. While resources remain abundant, the growth of autocatlytic activities provides increased resources that can also be tapped by peripheral processes (‘‘All boats rise with the tide’’).

As the inputs of resources approach their limits, however, centripetality does not relent, but rather begins to siphon resources away from other less-participatory sectors—a dynamic that might be termed ‘‘suck-up’’ (in contrast to the fiction called ‘‘trickle down’’). Minor players begin to suffer and dry up. Such a dynamic now seems to characterize the current state of global economies and gives rise to the drastic inequities cited by Sotolongo. Evidence thereof lies in the observation that for every dollar that changes hands in the physical economy (payments for goods and services) upwards of 50 are exchanged entirely within the financial sector (Lietaer 2001), giving impetus to the ‘‘Occupy’’ movement that is currently sweeping the world. In sustainable natural systems, a balance arises between circulation among peripheral sectors and dominant players (Ulanowicz 2009b). How to translate such a balance into economic terms should become a significant goal of complexity studies.

With all due humility, I am suggesting that for society to become sustainable, a third window must be translated into a ‘‘third way’’. Actually, this is not a new approach to countering global extremes. Pecci (1891), for example, explored this pathway in the XIX Century, and the challenges to his ‘‘subsidiarity’’ remain ever more pressing today. I see Pedro Sotolongo’s leadership of a significant Cuban initiative on Complexity Theory as emblematic of the widespread concern in countries on the periphery of the global economy about addressing the growing injustice inherent in the misdistribution of the world's wealth. Solving such problems must involve humankind as a whole and requires that participants from formerly adversarial ideologies seek common cause for the sake of a new humanity.

4 Ascendency Increase

As my colleague Stanley Salthe relates, he and I agree on most of the basic issues concerning evolution. He feels, for example, that what today passes for evolutionary discourse should be re-oriented towards developmental theory. I agree insofar as I believe that developmental theory has been unnecessarily excised from the evolutionary narrative. Rather than displacement, however, I would recommend balance. As I mentioned in connection with Grassie's remarks, I remonstrate that only one side of the Darwinian narrative is currently being told—the eliminative aspects that derive from competition. It is the neglected half of evolution—i.e., the growth side—that more resembles developmental theory and that deserves greater emphasis. Growth and development depend primarily upon mutualities and only secondarily upon competition. The role of competition in evolution remains essential; but, like the role of law, it is usually overstated.

4.1 Senescence

Like Sotolongo, Salthe quickly passes on to address two issues on which he feels we continue to differ, namely the phenomenon of senescence and the nature of the second law. Concerning senescence, I see our differences not so much as disagreement but rather as something not fully common to our individual perspectives. Salthe is a developmental biologist by training and career, whereas I matriculated as an engineer and pursued theoretical ecology as a profession. Stan's primary focus has been on the ontogeny of organisms, and I basically agree with his differentiation between development and evolution. The temporal scales that characterize the ecological perspective, however, fall between those pertaining to the organism and the epochal durations over which evolution transpires. Hence, ecology is neither fish nor fowl with respect to Stan's distinction of development from evolution.

The key question then becomes whether anything resembling senescence is apparent in the middle kingdom of ecology? It seems to me the issue could be argued either way: Those denying senescence in ecology might point to the ''climax'' configurations of ecosystems, such as those that typify the mixed mesophyte forests of the East coast of N. America. Prior to the arrival of humans, this ecotope apparently persisted for centuries on end with relative stasis in ecosystem functioning. On the other hand, ecologists point to the spruce-budworm ecosystems of the Pacific NW (Holling 1978) or the edaphic fire climax softwood forests of the American SE as examples of ecosystems that develop into a phase of ‘‘over-shoot’’ that is similar to senescence and which inevitably collapse back to an earlier successional stage.

Even those ecosystems that overdevelop do not, however, satisfy all of the 5 characteristics mentioned in the Salthe’s Table 1. It is questionable, for example, whether the energy flow densities of mature spruce forests ever drop below functional requirements. To be sure, old specimens of spruce trees will exhibit a drop in throughflow, but is it sufficient to jeopardize their functional requirements? I would submit that the onset of budworm infestation is not triggered by such energetic considerations.

In 3W I suggested that the ecosystem is a serendipitous arena in which to study the phenomena of growth and development: The scales of an ecosystem are generally larger and longer than those that characterize the rigidly scripted development of organisms. As well, ecosystems can continue to function in the absence of the human intentionality that drives social and economic communities. That is, one may study the growth and development of an ecosystem in abstraction from those complications that characterize these bracketing systems. Still, it remains difficult to identify ecosystems that closely resemble either senescent organisms or failing empires. Hence, I can only acknowledge this apparent lacuna in the ecological perspective and welcome Salthe’s suggestion as to how the notion of senescence might inform ecology.

4.2 Second Law

Our respective opinions on the endpoints of natural systems come closer to what might be called disagreement—at least at first glance. Salthe resolutely proclaims the primacy of the second law as the ultimate endpoint (final cause) of all change. I argue instead for a dualistic nature—a Heraclitean dialectic between ordercreation and entropic dissipation—a struggle between two tendencies of comparable ontological rank.

In the nearly 3 years since I finished writing 3W, I have entertained new perspectives on the concept of entropy and the nature of the second law, some of which I mentioned in my response to Grassie. In the light of my evolving understanding of entropy, I am hoping that Salthe and I may now be in a position to resolve our differences. I now accept how the second law might be regarded as over-arching, albeit only in terms of a new and untraditional interpretation as to what constitutes ‘‘entropy’’ (Ulanowicz 2011). The common image of entropy is one entirely of rank disorder, and the prevailing belief is that the second law condemns the universe to a ‘‘heat death’’—something akin to the 3-degree Kelvin background radiation. Such unremitting disorder is not, however, what one reads from Boltzmann’s mathematical formulation of increasing entropy, the results of his subsequent H-theorem notwithstanding.

It is now apparent that the boundary conditions that Boltzmann applied to his H-function were simplistic in the extreme. He used his H-formula to quantify a rarefied, homogeneous system of non-interacting particles (an ideal gas); and indeed under those contingencies, the only possible outcome is heat death. But the universe has never been a rarefied, homogeneous, unconnected system. It came at us as an incredibly dense and highly-interactive entity—astoundingly different from Boltzmann's mental construct. It happens that when one applies the Boltzmann H-function to more realistic systems, two alternative endpoints immediately become possible, each typified by the extremes shown in Salthe's Figures 2a and 2c. In the first (2a), almost no order is discernible, a state that resembles ''heat death''. At the other extreme (2c), however, one obtains a system of perfectly obligate constraint—a ''perpetual harmony''. Whence, increasing (Boltzmann) entropy more generally exhibits two possible endpoints—either heat death or perpetual harmonies (Ulanowicz 2009a).

That two endpoints are feasible is evidence of a dialectic taking place between two distinct drives having ontological parity—one towards order and the other towards dissipation. This new perspective on the second law does in fact appear to encompass all natural transactions. It does not follow, however, that order production is subservient to the generation of randomness even if, as Salthe maintains, the efficiency of effective work remains smaller than the rate of energy dissipation.[7] Properly framed, the essence of the second law resides in this asymmetry of rates, rather than in the extirpation of order altogether.

So I would agree with Salthe that the second law can be over-arching. In any event, I hold that it remains necessary to recognize that the second law is more complex than the force laws of physics and is nowhere as monist in nature as it historically has been portrayed.

5 Species as Processes

Anyone familiar with literary theory is quite aware that a text, once published, takes on a life of its own. How it will be interpreted depends largely upon the mindset of the reader. Often the slant of the reader results in an interpretation that is radically different from what the author had intended. Sometimes, however, there arises a resonance between what had been intended and what was received. I think this latter situation describes the reinforcing mutuality that characterizes A Third Window and Jeffrey Lockwood's own attitudes. Not only did Lockwood read the text in much the way I had intended, but he went on to expand the scope of those ideas. (Autocatalysis might be an appropriate metaphor to describe the dynamic.)

5.1 Networks as Configurations of Processes

Lockwood's elaboration was to take the elements of the ''ecological metaphysic'', which arose out of work with ecosystem flow networks, and apply it to the concept of species. I feel his extrapolation is on the mark, because it recapitulates an attitude that I implicitly adopted over my decades of work with ecosystems networks. Not having been formally trained in philosophy, I only gradually became aware that the

7 Data show that most ecosystems cluster around a ratio of 60% dissipation versus 40% effective work (Ulanowicz 2009b).

direction I was taking was towards the realm of process philosophy. It was relatively late in my game that I began to write about feedback among processes.

A few years before writing 3W, work with an undergraduate assistant, Alex Zorach, had inclined me towards the notion that species could be defined by the structure of the flows among them (Zorach and Ulanowicz 2003). What we did was to calculate the number of virtual nodes in a network that was implied by the overall topology of its arcs. (See the last equation on p. 71 in Zorach and Ulanowicz.) The number of virtual nodes is almost always smaller than the count of actual ones, many times by a significant amount. Unfortunately, the mathematics we used did not provide an actual mapping of the real species into the virtual ones (unlike the mapping I had been able to construct that coalesces actual species into virtual trophic aggregations [Ulanowicz 1995]).

For me the road to complementarity between objects and processes had been paved by Tellegen's Theorem (3W, p. 9). Tellegen's attention was on networks of thermodynamic processes. It is significant to mention that classical thermodynamics discriminates between ''state'' (reversible) variables and ''process'' (irreversible) variables. The former plays the dominant role in classical thermodynamics. Tellegen demonstrated, however, that if all the relationships between state and process variables happened to be linear, then the two categories of variables became wholly interchangeable—i.e., they then possess full ontological (and pragmatic) parity. Of course, the real world is replete with non-linearity, but that need not abrogate ontological parity between variable types, nor does it proscribe the possibility of gaining significant new insights by placing emphasis upon process variables.

Ecosystem flow networks constitute a subclass of thermodynamic networks. The implication of Tellegen's Theorem is that the nodes of such networks can be viewed as processes, or more accurately, as clusters of processes, which is precisely Lockwood's thesis. Although I have not focused my attention on species as processes, I have been made aware of the advantage of regarding organisms as configurations of processes by an anecdote related by my late friend, Tiezzi (2006).

Tiezzi, the owner of a Tuscan estate near Siena, had always to cope with deer that were eating his grapes and gnawing on his olive trees. In exasperation he resorted to shooting some of the deer, and in the immediate aftermath of killing one, he paused for a moment to contemplate what was missing in the dead deer that had been present in the minutes before? Its mass, form, bound energy, genomes—even its molecular configurations—all remain virtually unchanged immediately after death. What had ceased with death and was no longer present was the configuration of processes that had been coextensive with the animated deer—the very agency by which the deer was recognized as being alive. Organisms are, first and foremost, collections of processes.

5.2 Self-Entailment

Lockwood maintains that species are likewise configurations of processes, and I concur fully. Furthermore, I think that both propositions would be buttressed by one characteristic that organisms and species (as processes) share in common—they are both self-entailing. Rosen (2000) invoked category theory to distinguish between the actions of machines and organisms. The former are always open with respect to efficient cause.[8] The operation of machines always requires at least periodic intervention by human agency. Organisms, on the other hand, exhibit metabolism and require repair. Rosen demonstrated how metabolism facilitates repair and repair permits metabolism to continue. As to the efficient causalities involved, the organism constitutes a self-entailing configuration of action. Substitute ‘‘replacement’’ for ‘‘repair’’, and Rosen’s argument seems to translate to species as well. Lockwood hints he might be favorably inclined toward Rosen’s proposition when he cites Ghiselin’s remark that an economic firm ‘‘forms a closed system of a given kind’’.

5.3 Ecology and Evolutionary Theory

An important observation by Lockwood is that regarding species as processes helps to bridge the chasm that has separated ecology from evolutionary theory. Eugene Odum (1977) was similarly of the opinion that ecology would eventually provide insights into the larger nature of evolution, and it now appears that the process viewpoint connects the entire hierarchy of living behaviors, evolution—ecosystem—species—organism. As Bickhardt and Campbell (1999) noted, ‘‘It’s processes all the way down!’’

When I read Reiners and Lockwood’s perceptive appraisal of philosophy in ecology (after I had published 3W), their description of ‘‘constrained perspectivism’’ appealed to me immediately. Like Jørgensen (2002) and many other (but not nearly enough) ecologists, I believe that a pluralistic approach to ecosystem phenomena is absolutely necessary. But it’s not the pluralism so much as it is the notion of indefinite constraint that attracts me the most in their construct. Conventional positivist science deals almost entirely in crisp categories and deterministic laws, and I believe this restricted perspective leads to an egregious minimalism when it is applied to life. As Deacon (2011) argues, that which is missing (inaccessible by constraint) is a vital and necessary part of the description of life. Perhaps the significance of the missing is most obvious in the field of ecology, where the absence of a predator or a prey can have enormous effect on whether a species will continue in the evolutionary drama.

If recognition is not made of that which is missing, the picture of life cast by positivist explanation will be necessarily and significantly distorted. For the explanation of constraint and order is only one half of larger picture of life painted by Heraclitus—namely, that of nature as a dialectic between that which builds up and that which decays. Those who might fear that encompassing the missing would push science beyond quantification, should be comforted once they realize that the apophatic notion of entropy is eminently quantifiable. Its manifestation in networks as overhead is seen to be a prerequisite for the ability of systems to persist (Ulanowicz 2011).

8 Rosen’s entailment does not apply to other forms of causality—material, formal or final.

Also regarding pluralism, I welcome Lockwood's demonstration of how the three postulates of an ecological metaphysic might be recast in the light that reveals species to be processes. With his translation, he is recapitulating a longstanding tradition in thermodynamics, where the basic laws have repeatedly been recast in manifold ways without impugning the integrity of the discipline as a whole.

5.4 Process and Biodiversity

Finally, Lockwood anticipated Grassie's fourth query to me, which Lockwood might paraphrase as, ‘‘What are the practical consequences of treating species as processes?’’ I will remark here on only one of Lockwood's examples—how the process view might inform the discussion about biodiversity. Apropos, I note that Robert MacArthur (1955), one of the first ecologists to address ecosystem diversity, did so by invoking information theory to quantify the multiplicity of ecosystem processes, not populations or stocks. His was a propitious start to the discussion that went awry after impatience with measuring processes moved the conversation instead toward quantifying population numbers and biomass. Reverting to the conventional positivist mindset led ecology astray of the fundamental nature of diversity—namely, the lack of constraint. By hindsight it is now clear why no positivist model has been able to justify the conservation of biodiversity—such a task is oxymoronic. Readopting the process point of view and quantifying the overhead among processes (as MacArthur had initially attempted) should lead to a considerably more fecund treatment of the issue (Ulanowicz 2009b).

Whether treating species or ecosystems, the process viewpoint reveals a host of new and unexplored vistas on nature, several of which are likely to afford significant new insights into the phenomenon of life.

6 A Theology of Evolution?

John Haught takes the discussion on 3W to where most scientists do not wish to go—into the dialogue between science and theology. It's probably fair to say that most scientists believe that theists have absolutely nothing to contribute to science and some vociferously oppose any implied contact between science and religion, no matter how tenuous. Haught and I obviously believe otherwise, which should be no particular surprise, given as how we were both raised in a sectarian tradition that was decidedly instrumental in the inception of the scientific revolution.

6.1 False Absolutes?

Writing out of that tradition, Wojtyla (1988) provided an amazingly concise and accurate description of the conversation between the two ways of knowing: ‘‘Science can purify religion from error and superstition. Religion can purify science from idolatry and false absolutes’’. Akin to a Hegelian dialectic, the relationship between participants is confrontational at the superficial level, but the deeper one probes, the more mutually enriching grows the dialogue. For example, it should give pause to the materialistic investigator who revels in tearing down myths and superstitions that material itself is a poor choice for the starting point to apprehending nature, arising as it did well along (logarithmically speaking) in the development of the physical universe.

In their own turns, the Newtonian and Darwinian narratives have spawned distinct sets of absolutes, which (in the falsificationist tradition of the scientific method) must be repeatedly subjected to questioning. For example, the Newtonian school adheres strictly to a closed, mechanical view of natural events, while many proponents of Darwin regard all forms of nature as the consequences of deterministic law and blind chance. It is to a degree ironic that the two schools should bear the names of these particular individuals, as Newton has often been described as the ‘‘last Medieval Man’’ because of his known affinity for alchemy and religion, whereas Darwin remained an aficionado of Newtonian methods.

Like with Lockwood, so also with Haught, the text of 3W has taken on a life independent of its author. Although I have a habit of referring to various schools of thought as ‘‘narratives’’, I had never made a connection between process ecology and drama. The reader can only imagine my amazement when I read Haught’s description of the fundamentals of a drama—contingency, continuity and time, which correspond remarkably with my postulates—chance, self reference and history. I argued above how chance is an element in the broader category that is contingency. Self-reference (in the form of autocatalysis) can give rise to selfpersistence, i.e., continuity. Finally, history is what is preserved over time.

It is my opinion that false absolutes are behind most of the ostensible conflicts between science and religion. I also warn that these same false absolutes poorly serve the advancement of science. Haught and I independently comment on the schizophrenia that ill-considered dichotomies induce: Haught comments, ‘‘After looking fleetingly through the second window, they hastily seek clarity by moving back to the first, where they attempt to resolve the annoyance of contingency into hard rock necessity…’’ In *Ecology, the Ascendent Perspective* (Ulanowicz 1997), I characterized the necessity in neo-Darwinism to shift constantly back and forth across many order of magnitude as downright schizoid.

None of which is to guarantee that science and religion will over time be of one accord. Each movement advances by fits and starts, and on occasion new apparent discords are certain to arise. Furthermore, it actually profits both endeavors to remain independent, leading to what Haught called ‘‘a more promising engagement of science and theology’’. To think otherwise is to exhibit what Haught (2000) terms ‘‘metaphysical impatience’’. The resolution of the drama is nowhere in sight and will likely endure for an interval analogous to what evolutionary theorists call ‘‘deep time’’. Meanwhile, patience seems to be a virtue much in demand.

I have encountered scientists who hold tenaciously to the sufficiency of law, because they feel that any other predicate would seriously weaken the morale of the scientific community. I (and I think Haught as well) would respectfully but firmly reject such pessimism. It doesn’t nurture one’s religious faith to cling to a particular belief, when everything one encounters is informing otherwise. Rather, participating in a transcendental drama provides meaning and direction for the theist. Likewise, it will not sustain a scientist’s morale continually to have to make excuses for a tenet that can no longer stand the test of scrutiny. Participating in the drama of nature is more likely to sustain scientists' enthusiasm. Naturalist or theist, the common outcome should be the note on which both A Third Window and Haught's critique ended—one of hope!

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References

Ayala FJ (2009) Darwin's revolution. Presented at biological evolution: facts and theories. Pontifical Gregorian University, Rome, 3 March

Bickhardt MH, Campbell DT (1999) Emergence. In: Andersen PB, Emmeche C, Finnemann NO, Christiansen PV (eds) Downward causation. Aarhus University Press, Aarhus, pp 322–348

Chaisson EJ (2001) Cosmic evolution: the rise of complexity in nature. Harvard University Press, Cambridge

Deacon TW (2006) Reciprocal linkage between self-organizing processes is sufficient for selfreproduction and evolvability. Biol Theory 1(2):136–149

Deacon TW (2011) Incomplete nature. W.W. Norton & Co., New York

Depew DJ (2011) Accident, adaptation and teleology in Aristotle, Empedocles and Darwinism. In: Auletta G, Leclerc M, Martinez RA (eds) Biological evolution: facts and theories. Gregorian and Biblical Press, Rome, pp 461–478

Haught JF (2000) God after Darwin: a theology of evolution, 2nd edn. Westview, Boulder

Hoffmeyer J (2008) Biosemiotics: signs of life and life of signs. University of Scranton Press, Scranton

Holling CS (1978) The spruce-budworm/forest-management problem. In: Holling CS (ed) Adaptive environmental assessment and management. International series on applied systems analysis, vol 3. Wiley, Hoboken, NJ, pp 143–182

Jørgensen SE (2002) Integration of ecosystem theories: a pattern. Ecol Environ 3:365–396

Juarrero A (1999) Dynamics in action: intentional behavior as a complex system. MIT Press, Cambridge

Lietaer B (2001) The future of money. Century, London

Lietaer B, Ulanowicz RE, Goerner SJ (2009) Options for managing a systematic bank crisis. Sapiens 1(2):1–15

MacArthur RH (1955) Fluctuations of animal populations and a measure of community stability. Ecology 36:533–536

Odum EP (1977) The emergence of ecology as a new integrative discipline. Science 195:1289–1293

Pecci V (1891) Rerum Novarum: on capital and labor. Encyclical of Pope Leo XIII. <http://www.papalencyclicals.net/Leo13/l13rerum.htm>

Popper KR (1990) A world of propensities. Thoemmes, Bristol

Prigogine I (1978) Time, structure and fluctuations. Science 201:777–785

Rosen R (2000) Essays on life itself. Columbia University Press, New York

Tiezzi E (2006) Steps towards an evolutionary physics. WIT Press, Southampton

Ulanowicz RE (1995) Ecosystem trophic foundations: Lindeman exonerata. In: Patten BC, Jorgensen SE (eds) Complex ecology: the part-whole relation in ecosystems. Prentice Hall, Englewood Cliffs, pp 549–560

Ulanowicz RE (1997) Ecology, the ascendent perspective. Columbia University Press, New York

Ulanowicz RE (1999) Out of the clockworks: a response. Estuaries 22:342–343

Ulanowicz RE (2004) Ecosystem dynamics: a natural middle. Theol Sci 2(2):231–253

Ulanowicz RE (2009a) Increasing entropy: heat death or perpetual harmonies? Des Nat Ecodyn 4(2):1–14

Ulanowicz RE (2009b) The dual nature of ecosystem dynamics. Ecol Model 220:1886–1892

Ulanowicz RE (2011) Towards quantifying a wider reality: Shannon Exonerata. Information 2:624–634

Ulanowicz RE, Hannon BM (1987) Life and the production of entropy. Proc R Soc Lond Ser B 232:181–192

Ulanowicz RE, Goerner SJ, Lietaer B, Gomez R (2009) Quantifying sustainability: resilience, efficiency and the return of information theory. Ecol Complex 6:27–36
Wheeler JA (1980) Beyond the black hole. In: Woolf H (ed) Some strangeness in the proportion. Addison-Wesley, Reading, pp 341–375
Wojtyla K (1988) Letter of His Holiness John Paul II to George V. Coyne, 1 June 1988
Zorach AC, Ulanowicz RE (2003) Quantifying the complexity of flow networks: how many roles are there? Complexity 8(3):68–76