Reckoning the nonexistent: Putting the science right

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ABSTRACT

Patten (2014) focuses upon some obvious conflicts between environmental action and the science of ecology and asks whether either should be revised to achieve better accord. It appears that both need to be reconsidered, but it is the conventional notion of science that seems more in need of emendation. The materialist/mechanist metaphysics of conventional science renders it unsuitable for the interpretation of ethics and inadequate to the full treatment of the phenomenon of life. Fortunately, the study of ecological networks provides a natural introduction of the apophatic (that which does not exist) into science, because it makes possible the quantitative parsing of the organization inherent in a network from its residual flexibility (an apophasis, or lack of constraint). Data suggest that both are necessary for sustainability, and methods for achieving a balance between the opposing attributes are outlined. The conventional mechanistic picture of the ecological world as a noisy clockwork must be transformed into the metaphor of a dialectic between the buildup of autocatalytic constraints and the entropic decay of system organization. Enduring configurations of mutualistic contingencies appear more relevant to the explanation of ecosystem behavior than is classical dynamical theory. With this transition to a more encompassing metaphysics, most of the inconsistencies observed by Patten evaporate. For example, the full picture reveals that there are contexts under which maximum power should be allowed full reign, while other conditions call for the environmentalist's conservative approach.

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1. Major disconnects

Bernard Patten, earlier in this Special Edition identifies several points of major dissonance between key projects of the environmental movement and the science of ecosystem behavior. He notes, for example, that considerable efforts around the globe have been mounted to conserve biodiversity, while the theoretical support for such action is very tenuous, at best. The principle of maximum power generation is purported to be driving much of ecosystem dynamics (Odum, 1971), and the dissipation it generates is often quite destructive locally. He argues, however, that such local upsets often contribute to greater welfare at the next higher level. Why, then, work to inhibit local instances of maximum power generation (e.g., eutrophication)? The dynamics of maximum power apply as well to Neoliberal economics, where it is almost axiomatic that local maximization of profit will contribute to the common good. Why do so many organizations work to achieve peace, when wars create ever larger alliances within which conflict is significantly

mitigated? Why aim to make human society sustainable, when the scientific consensus is that biological systems are never in equilibrium?, etc.

Patten makes it very clear that he is not advocating abandonment of environmental and humanitarian initiatives. Rather, he is pointing to how value-free science does not square with many human concerns. He aims more toward putting both science and public consensus to the test – much in line with Popper's call for continued attempts to falsify hypotheses. Falsification is a notion to which everyone pays lip-service, but very few ever practice. Patten, then, is courageously following Popper's exhortation to seek out and confront inconvenient dissonance.

To paraphrase Patten's questions: "Is environmentalism misguided, or is science inadequate to evaluate the benefits of contemporary environmental action?" To be sure, one can cite examples that speak to either side of this issue, but because the subject of this Special Edition is ecological science, I wish to focus on the shortcomings of contemporary theory. Regarding the adequacy of science, I begin by recalling the answer that Augustine of Hippo gave when he was asked if miracles violated natural laws? In effect he said, "No, we just don't know enough about natural laws!" Of course, miracles remain outside of science, but the point I wish to make is that we are still in need of Augustine's Fourth Century humility, despite our advanced notions of natural laws

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and the enormous benefits wrought by science over the past three centuries.

To allay any possible misgivings on the part of the reader, let me affirm now that I do not think that contemporary science is necessarily wrong – just that it remains (perpetually) incomplete, and that accepted metaphysics greatly exaggerate the role of universal laws in the origins of natural living systems.

2. Observing with one eye only

It is central to the scientific method that our body of knowledge always remains incomplete and evolving. With a slight touch of irony, I wish to suggest that, although most scientists do recognize the incompleteness of their own field, the greater majority remain unaware that nature itself is incomplete. Were it otherwise, science would not remain almost exclusively positivistic (material/mechanical) in scope. As it is, contemporary science is didactic and focuses narrowly on the palpable, on observable regularities. It pays scant regard to the arbitrary and virtually none at all to that which is absent. Bateson (1972), for example, remarked on the preoccupation of physics with the palpable, and that it is only rare exceptions, like the Pauli Exclusion Principle, that mention what is not or cannot be. More recently, Deacon (2011) underscored Bateson by highlighting the role that the missing plays in initiating and sustaining change.

Focus upon the palpable is, of course, natural and understandable. The arbitrary and the missing tend to be unattractive and difficult to describe, much less to quantify. With simple systems, it usually has been possible to isolate and ignore irregularities by creating artificial laboratory situations (Popper, 1990). But with complex systems like ecological communities, there simply is no ignoring that which is absent. If, for example, a particular resource or predator of a given population is absent, it becomes a matter of life or death to that species. The conventional way of accounting for the missing is to relegate it to the boundary statement for the problem. If, however, the arbitrary or the missing happens to be integral to the system dynamics, it becomes a significant distortion of reality to remove it to the exogenous world.

3. Engineering – a different metaphysics

My point is that it is entirely possible to quantify the indeterminate and/or the absent as *endogenous* aspects of complex systems. At first, such a task strikes one as absurd and oxymoronic – to quantify that which is not?! Such quantification might seem especially perplexing to those trained always to approach problems in reductionistic fashion, which has been the experience of most biologists. Engineers, however, feel no compulsion always to invoke reductionism. Their role in society does not permit them to wait for reductionist explanations. They are forced daily to confront practical problems by searching for quantitative regularities that appear and persist in the absence of any knowledge about detailed events – an approach they have labeled "phenomenology" (which biologists frequently disdain as empiricism). It is through phenomenology, however, that that which is absent becomes apparent.

Perhaps phenomenology is most frequently encountered in the guise of engineering "black-box" methods of problem solving. The most significant example of phenomenological science, however, is thermodynamics. The basic laws and relationships of thermodynamics were discovered without any knowledge whatsoever about the actions of individual molecules. In fact, it was not even necessary to know that atoms and molecules exist! By way of example, if during my own training as an engineer, I should use either the word "atom" or "molecule" in response to any question on thermodynamics, that answer would categorically be marked incorrect.

My mentors imposed this restriction to emphasize that the laws and inter-variable relationships of thermodynamics remain solidly and wholly entailed by phenomenology.

Many remain unaware of how the development of thermodynamic principles during the 19th Century placed the atomic theory at risk. How could small particles, presumably obeying reversible dynamics, behave irreversibly in the aggregate? This enigma underscored a dictum that many would prefer to ignore: If a theory contradicts established phenomenology, it is always the theory that is at risk, not the phenomenology. To operate otherwise would be to engage in ideology, not science. That thermodynamics is portrayed today by physicists as a form of molecular statistical mechanics represents an attempt by physicists to maintain the ascendancy of a reductionist physics that many engineers know is helpful at times, but is by no means necessary.

Of course, the macroscopic approach is not foreign to ecology. All ecologists recognize the obligate role of genes in ontogeny, and many projects in autecology deal with the expression of genetic characteristics. It would be foolhardy, however, to predicate the behavior of whole ecosystems on genomes (Stent, 1981).

It will come as a further surprise to many non-engineers to learn that one can uncover significant factors in a system's operation in the absence of any knowledge about its specific dynamics. The "Buckingham-Pi Theorem", which undergirds the discipline of "dimensional analysis", allows the engineer to sift through the characteristic parameters of a system and identify key system processes without having any knowledge of the dynamical form of those processes (Buckingham, 1915; Long, 1963).

4. Reckoning the indeterminate

This empirical mindset of the engineer provides an avenue toward quantifying that which is missing. The approach, however, is indirect and relativistic, because quantifying what is missing is not possible in any absolute sense. A relative measure of what is missing is nonetheless almost always feasible.[1] Thus, we begin by focusing not on what is absent, but rather on how much of an attribute is present. For example, we derive a metric of the extent to which the internal processes of a system are constrained by one another. We then calculate this metric for two different system configurations. By difference, then, it becomes possible to calculate how much constraint is *lacking* from the lesser organized system with respect to the more organized form.

To illustrate such relativistic computation, I turn to the metaphor of the network. Conventionally, a network is assumed to represent the constraints that bind various elements into a functioning system – and this it does. The metaphor does not end there, however. The network also portrays the ways in which *indeterminacy* is amalgamated with the constraints that bind the system. Consider, for example, the web in Fig. 1 depicting energy transfers in an oyster reef community (Dame and Patten, 1981). Medium at any node of the network cannot flow directly to all other nodes. For example, if energy is resident in the deposited detritus, it can proceed only to the deposit feeders, the microbiota or the meiofauna, and not anywhere else. Implicit and unspecified constraints prohibit energy from flowing directly to the remaining compartments.

But such constraint is only half the story. At the same time, it is not determined to which of the allowable consumers the next quantum of energy will flow. For example, it seems impossible to say whether a fish predator will next consume a filter feeder or a deposit feeder. Most probably believe that, although one remains

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[1] Some thermodynamicists will recognize this sentence as a restatement of the third law of thermodynamics.
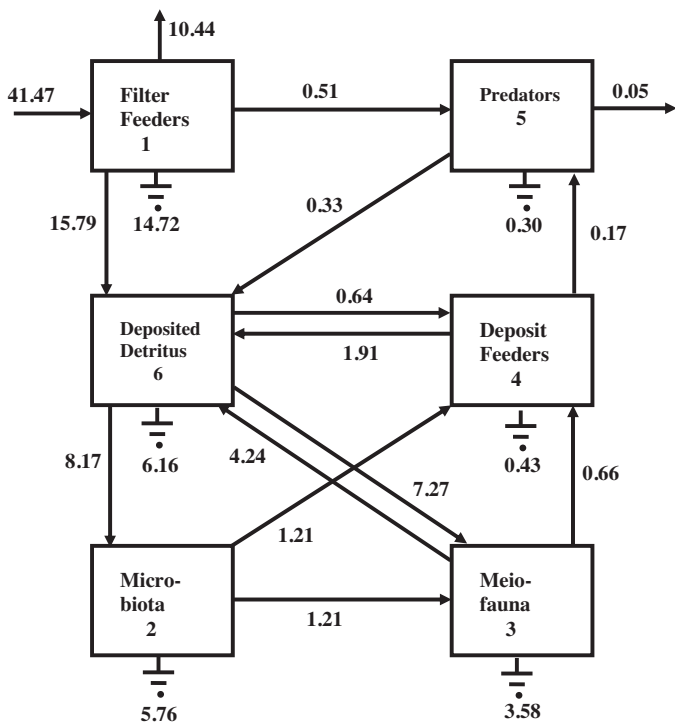
Fig. 1. The trophic exchanges of energy (kcal m^{-2} y^{-1}) in the Oyster Reef Community (Dame and Patten, 1981). Arrows not originating from a box represent exogenous inputs. Arrows not terminating in a box portray exogenous outputs. Ground symbols represent dissipations.

uncertain as to what the next prey will be; prediction, in principle, remains possible. Indeed, in particular cases prediction might be feasible, but I will argue later in this essay that, in the general case, prediction is clearly impossible. The idea of such indeterminacy will likely be difficult for many to accept, but I hope to convince the reader that, unless one faces up to the reality of indeterminacy, an adequate understanding of the dynamics of life cannot be achieved.

In Patten's essay he correctly refers to networks as describing how causality is propagated through the system. Networks do more, however. They also propagate indeterminacy across the system. (Anyone who doubts this statement has probably never worked with electrical circuits and has not been confounded by the ways by which point source noise can propagate over the system.)

So if both constraint and indeterminacy are present in a network, how can an investigator apportion the amount by which each attribute is present in any particular configuration? Toward this end, we begin by denoting the magnitude of any transfer between populations i and j as T_{ij}. We further indicate a summation over any subscript of T_{ij} by replacing that index by a dot. (For example, $T_{.j} = \Sigma_i T_{ij}$, or $T_{..} = \Sigma_{i,j} T_{ij}$.) As a convenient measure of the potential complexity of our network we may employ the Shannon–Wiener index of flow diversity

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

Some of this diversity pertains to the constraints themselves. One could resort to conventional statistics to investigate the degree to which the various T_{ij} correlate with one another. The T_{ij}, however, are not distributed in normal fashion (Ulanowicz and Wolff, 1991), and so we are better off seeking a similar measure expressed in terms of logarithms. The logarithmic measure analogous to

correlation is the average mutual constraint, A, expressed in terms of the T_{ij} as

$$A = \sum_{i,j} \left(\frac{T_{ij}}{T_{..}} \right) \log \left(\frac{T_{ij} T_{..}}{T_{i.} T_{.j}} \right).$$

It can be demonstrated that $D \geq A \geq 0$ (Ulanowicz, 1986, Chapter 5).

If A measures on average how tightly the T_{ij} are bound to one another, then the difference $\Phi = (D - A) \geq 0$ becomes a measure of the degree to which the T_{ij} remain independent of each other, i.e., the *lack* of constraint among the flows. A little algebra reveals that

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

This decomposition, $D = A + \Phi$, defines the relative amounts of constraint and indeterminacy that exist among the T_{ij}.[2] The measure A gauges in didactic fashion the palpable (even if undescribed) constraints in the system. The complementary lack of constraint, Φ, will be characterized by the adjective "apophatic", in that it represents something that does *not* exist.[3] (The constraints that are missing become an "apophasis" [n.]) I am suggesting that the distinction and interplay between didactic and apophatic concepts is key to understanding many of the enigmas that cloud current biological theory. For the Dame and Patten network in Fig. 1, $D = 3.216$, $A = 1.402$ and $\Phi = 1.814$ (bits[4]).

Now that we can quantify the degree of didactic vs. apophatic elements inherent in any network, we can apply our measures to observed ecosystem networks to investigate actual distributions. Before doing so, however, we first consider in more detail the origins of and the roles played by constraint and flexibility.

5. The origins of constraint

It is widely accepted that most biological order arises via the Darwinian evolutionary scenario. Darwin originally presented his narrative in almost Heraclitean format – building up (growth and mutation) vs. tearing down (natural selection). In the contemporary Neo–Darwinian version, however, the role of growth in the transaction has almost vanished from evolutionary discourse (likely due to an inability to articulate the drive behind growth). While change (mutation) is commonly regarded to occur within the system, the contingencies of natural selection are presumed to act (in Newtonian fashion) from outside. Putting the science right involves reviving the Heraclitean format to emphasize growth once again and to reposition selection so that it can act within the system as well as from outside.

To imagine how internal selection might arise, we consider the phenomenon of autocatalysis. Fig. 2 depicts three actors that are related in cyclical fashion, each receiving benefit from its upstream partner and providing benefit to its downstream counterpart. Implicit in this configuration resides a *positive* form of

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[2] The alert reader may recall that the nonexistent can be quantified only in a relative sense and so ask where is the comparison? The comparison was made implicitly between the input configurations and the output arrays of the various nodes (Rutledge et al., 1976).

[3] The variable Φ in the decomposition is referred to in information theory as the "conditional entropy". That entropy refers not to a palpable thing or positive attribute may explain why so much confusion and debate persist over the nature of entropy.

[4] The units "bits" imply that the base of the logarithms was 2. The units would be "nats", if the natural base (e) had been employed and "hartleys", if the base had been 10.
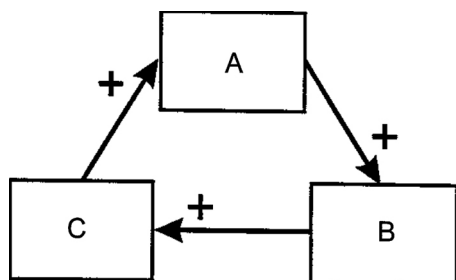
Fig. 2. An autocatalytic configuration of three entities.

selection. For example, if an arbitrary change occurs, say in *B*, and it either facilitates *B*'s use of the benefit from *A* or accelerates its promotion of *C*, then *B* will receive more sustenance from *A* (be augmented) via the cycle. Conversely, arbitrary changes that diminish either interaction of *B* with *A* or *C* will cause *B* to receive less reward from *A* (be depreciated). It is important to note that this mode of selection applies as well to changes in any exogenous resources received by a participant. That is, should a change occur in *C* (or any of the participants) that allows it to obtain more of an external resource to increase its performance, that change will be rewarded. The end result is the phenomenon of *centripetality* (Ulanowicz, 1997), whereby internal selection pulls progressively more resources into the orbit of autocatalysis (usually at the expense of non-participating elements). (See Fig. 3.)

Although rarely mentioned among the attributes of life, the phenomenon of centripetality is essential to living systems. It is the crux of growth and the motive behind maximum power. According to Russell (1960), what he called "chemical imperialism" (i.e., centripetality) provides the drive behind *all* of evolution. It is more fundamental even than competition, because competition cannot happen unless autocatalysis first exists at the next level down (Ulanowicz, 2009a,b). As the autocatalytic configuration matures, it binds its participants ever more tightly to one another (increasing constraints). Autocatalytic action is the major contributor to increases in A, our didactic measure of growth.
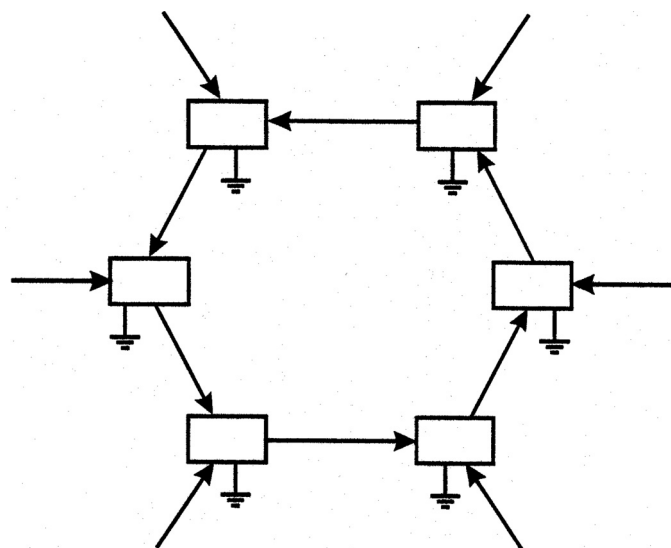

Fig. 3. Centripetality: the tendency of an autocatalytic cycle to pull resources into its orbit.

6. The necessity of freedom

Autocatalysis, if left unconstrained, would result in a system that is highly efficient, but very rigid – one with almost no flexibility. Flexibility, or the *absence* of constraint, is an apophatic concept and can be reckoned, as shown above, by the measure Φ. This lack of constraint pertains not only to flexibility within the nodes, but as well to any redundancy in the pathways between nodes. The ability of a system to reconfigure itself by re-routing flows over redundant pathways is presumed to facilitate the persistence of systems in the face of arbitrary perturbations (Hill and Wiegert, 1980).

Some degree of apophasis is required by all living systems in order to persist. It happens that greater biodiversity (more and varied nodes) also contributes to pathway redundancy and hence to system sustainability. The accompanying flexibility clearly belongs on the apophatic side of the ledger. It now becomes obvious why it has been so difficult to justify the conservation of biodiversity using didactic models within a positivist science.[5]

Constraint and the lack thereof are agonistic by definition. Unfortunately, this opposition is not well appreciated by many who persist in believing that one can simultaneously achieve high efficiency with high reliability. At any given level of complexity, an increase in one attribute implies a decrement in the other. This does not mean that a given event that contributes to one attribute at a particular level might not also contribute to its opposite at another level. That is, there is a Hegelian character to the interaction between the didactic and the apophatic in any system. For example, apophatic contingencies that detract from (didactic) efficiency in a biological system over the short term sometimes can be utilized as part of system adaptation and sustainability over the long run. By the same token, highly organized (didactic) systems generate more dissipation (apophasis) per-capita for their maintenance. The same Hegelian nature pertains as well to Patten's Janus Hypothesis, whereby win–lose interactions at the local level translate into win–win results at the whole system level.

7. Freedom and constraint in ecosystems

We now focus our attention upon the relationship between the didactic and the apophatic in ecosystems. We ask, for example, whether the ratio between the opposing attributes changes in any regular way among different ecosystems? To investigate this question, we define a "degree of organization", *a*, as that fraction of the diversity of processes which is expressed as constraint, i.e., $a = A/D = A/(A + \Phi)$. I had originally anticipated ecosystems to mature in the direction of increasing *a* (Ulanowicz, 1980); however, I subsequently discovered that values of *a* compiled from disparate ecosystems at various stages of development appeared to show remarkably little variation. That ratio appeared to cluster closely around a value of $a \approx 0.40$ for all networks that had been reasonably well articulated (i.e., those with $n > 13$) (Ulanowicz et al., 2009).

One sees the clustering in Fig. 4, where the values of *a* for a collection of 16 well-articulated ecosystem flow networks are plotted along the abcissa. On the ordinate is plotted a measure of the potential for evolution, F, defined as the product of the degree of organization, *a*, times a corresponding measure of its disorganization ($-\log[a]$).[6] The product $F = -ea \ln(a)$ measures the ability of a system to evolve, because an adaptive evolutionary system

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[5] Empirical evidence does exist; however, supporting the notion that biodiversity fosters resilience (e.g., Tilman and Downing, 1996, or Naeem and Li, 1997).

[6] That is, the didactic is arrayed against the apophatic. One might reasonably inquire why the quantity $(1 - a)$ was not chosen as the measure of disorganization? The choice of the negative logarithm follows the intuition of Ludwig von Boltzmann,
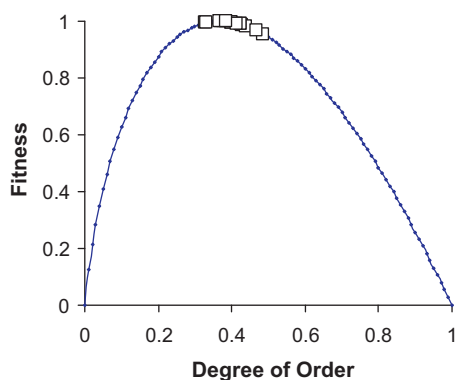
Fig. 4. The degrees of order and corresponding magnitudes of fitness, *F*, for the subset of 16 ecosystem flow networks that consist of more than 13 compartments.

requires sufficient organization (*a*) to select from among its necessary residual of unconstrained configurations (−ln[*a*]). (The factor *e*, the natural base of logarithms, has been inserted to normalize *F* so that $F_{max} = 1$ at $a = 1/e$.) We observe a cluster of system networks around $a \approx 0.4$, which lies just to the right of maximal *F* (Ulanowicz, 2009b).

That most functioning ecosystems appear to persist around a "sweet spot" between the extremes of no organization and absolute rigidity suggests a new interpretation of the notion of sustainability. The data suggest that observed natural systems maintain a propitious balance between sufficient constraints to hold the system together and adequate flexibility to allow adaptation to unforeseen circumstances. It is important to note that this balance is not an equilibrium in the usual sense of the word. It simply indicates that ecosystems congregate near the point where they are best poised for further evolution. The relationship between the whole-system attribute *a* and the various constituent flows, T_{ij}, is inherently very-many-to-one, so that there exist an infinity of ways that the multitude of system nodes can continue to change while at the same time holding the system property, *a*, nearly constant.

As with any balance, this one consists of countervailing drives that hold each other in check. Balancing resembles a cybernetic process, in that the positive feedback in autocatalysis impels the system toward maximum power, constantly pushing it toward the right in Fig. 4. At the same time entropy-like disturbances and the negative feedbacks they engender continuously degrade system organization and move it toward the left, in the process providing new opportunities for further system adaptation and evolution. The resulting *Via Media* is removed from the extremes of $a = 0$ and $a = 1$. It is extremely important to note that a monist positive-feedback drive (unbridled growth) would push the system significantly beyond the balance point and would wreak disastrous consequences. The negative feedbacks that ecologists identify with the establishment of a carrying capacity help to prevent this outcome.

With these points in mind, the answer to Patten's "Janus" question – why not allow maximum power to play out its role without intervening? – now becomes apparent. Whether or not to intervene depends upon the existing degree of organization in the system. If *a* is significantly below the natural balance point, then indeed maximum power should be allowed to move the system toward balance. In accord with the Janus Hypothesis, non-intervention will then promote network synergism and foster a win–win, life-and-environment relationship. If, however, the system happens to be

well to the right of the balance, then allowing maximum power to push the system further toward the right could spell disaster. In such case, intervention would be in order. Patten's "Catch-22" conundrum warns, however, that intervention could run the risk of interfering with network synergism and might wreak unseen negative consequences across the broader systemic network.

I note as how market efficiency fosters maximum power at work in economic systems. It has been suggested that Neoliberal prescriptions allow market efficiency to drive the economy beyond its balance point and toward inevitable catastrophe (Goerner et al., 2009). Most economies eventually recover, only to repeat the collapse in a continuing cycle of boom and bust. The cycle, as it occurs in smaller economies, can at times be manipulated by players in the larger economic powers to the advantage of the latter, thereby heightening global economic disparities (Klein, 2007). Relief from such upheavals might be achieved by interjecting alternative currencies into the marketplace (Lietaer et al., 2010). From a network perspective, the redundancies that accompany multiple currencies augment *Φ* and thus contribute to the apophatic buffering against excessive market efficiency. Finally, as regards economics, it should be noted that communities to the right of natural balance are characterized by great inequities in wealth, whereas those far to the left are too equitable to be productive. As with ecosystems, a healthy economy is one not driven to extremes by any monist ideology (Pecci, 1891).

The notion of balance applies as well to biodiversity. Diversity characterizes the left side of the balance. If a system becomes too efficient and too well-adapted to benign environments, biodiversity will atrophy, and autocatalysis drives the system to the right of the balance point, where it becomes vulnerable to perturbations. To avoid inevitable catastrophe, the conservation of biodiversity becomes necessary (*cf.* Jørgensen, 1992).

For personal reasons, I feel compelled to address Patten's reference to the social benefits of war. It is true that war tends to coalesce ever larger communities of interest. But this process is one of "peace through ascendancy", whereby the social network is forced to the right. The losers (the vanquished and the oppressed) in this outcome become legion. There is, however, another route to peace – the ancient Hebraic notion of "peace through justice". Although justice is usually envisioned as strict equality, it can alternatively be framed as a state of equi-partition, as might exist at the balance point we have been describing – a world in which system constituents are not strictly equal, but see much the same opportunity for expression and further evolution. The desirability of such a state prompts efforts to discover how one might guide a system toward such balance.

8. Finding balance

While qualitative prescriptions appeal to the intuition, an engineer always seeks to quantify directions. If the system of one's concern is removed from propitious balance, where in the system is the best place to intervene? To address this question we introduce the concept of system robustness, *R*, which is defined simply as the system fitness, *F*, scaled by the total system throughput, ($T_{..}$) (i.e., $R = T_{..}F$). We notice in Fig. 4 that for ecosystems, the balance point in *a* lies just to the right of the maximum of the function $F = -ea \log(a)$. In order to generalize the position of the balance, we now introduce a parameter *β* (in good phenomenological fashion) to make the maximum of *F* coincide with the empirical balance. To be more exact, we re-define F such that $F = -a^{\beta} \log(a^{\beta})$. Then when $\beta \approx 1.28$, the maximum of *F* occurs at $a = 0.40$.[7]

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who saw nature as weighted toward many events of small magnitude. The quantities $(1 − a)$ and $−\log(a)$ are related uniformly over the interval $1 > a > 0$.

[7] Each point in the interval, $0 < a < 1$ corresponds to a *β* in the range $0 < \beta < \infty$, so that the maximum can be moved to anywhere in the allowable range of *a*.
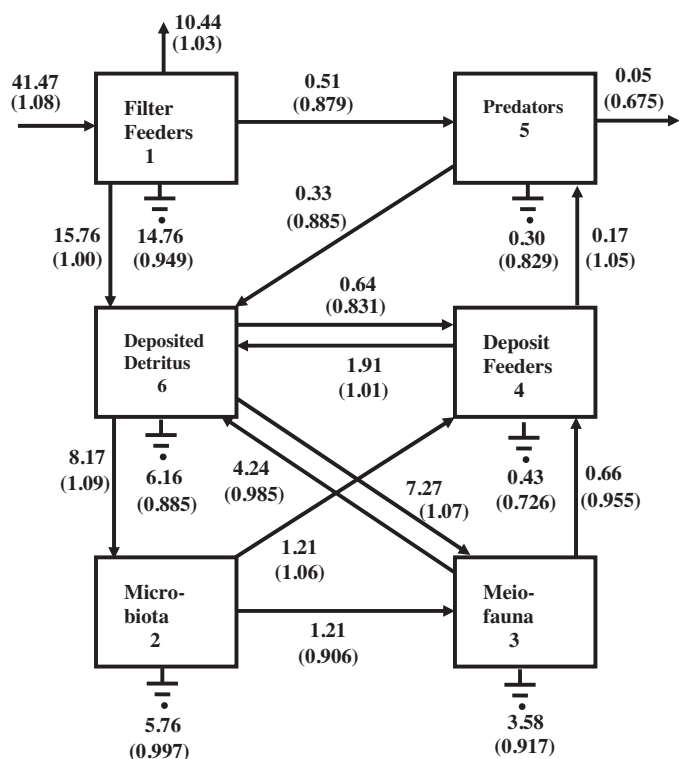
Fig. 5. The values of the marginal contributions (in parentheses) of the flows in the Oyster Reef Community (Fig. 1).

Fig. 6. Hypothetical eutrophication in the Oyster Reef Community, represented by adding 100 units to the pathway → 1 → 6 → 2 →. The revised marginal contributions appear in parentheses.

Now, it is straightforward, albeit algebraically messy, to calculate the sensitivity of R with respect to any particular flow, T_{ij}:

$$\frac{\partial R}{\partial T_{ij}} = F + \frac{T_{..}F'}{D}\left\{\ln\left[\frac{T_{ij}T_{..}}{T_{i.}T_{.j}}\right] + a\ln\left[\frac{T_{ij}^2}{T_{i.}T_{.j}}\right]\right\},$$

where

$$F' = -e\beta a^{\beta-1}[\ln(a^\beta) + 1].$$

Each sensitivity $\partial R/\partial T_{ij}$ represents the marginal contribution of T_{ij} toward moving the system in the direction of propitious balance. We note that *at* the balance point, $R_{\max}$, all $\partial R_{\max}/\partial T_{ij} = 1$, so that each flow is contributing a proportionately equal share to system sustainability (e.g., "peace through justice"). If $\partial R/\partial T_{ij} < 1$, then T_{ij} is not contributing optimally to balance and should be diminished roughly in inverse proportion to the sensitivity coefficient. Conversely, whenever $\partial R/\partial T_{ij} > 1$, the given flow should be augmented in proportion to its sensitivity so as to move the system toward balance.

By way of example, Fig. 5 re-depicts the network of trophic transfers in the oyster reef community of Fig. 1, but where the marginal contributions of each flow have been added in parentheses below each actual magnitude. Because the value $a = 0.436$ for this community is only slightly greater than the ensemble mean for ecosystems (0.401), all the marginal contributions by the various flows are close to one.

We now explore how marginal contributions would respond if maximum power were to push the system to the right, beyond its propitious balance. To model such an imbalance, in Fig. 6, I have added 100 units of flow to each transfer in the pathway → filter feeders → deposited detritus → Microbiota → dissipation. (If the authors had included algae in the system in front of the filter feeders, the amended system would then have depicted a typical eutrophic ecosystem.) We now notice that the resulting marginal
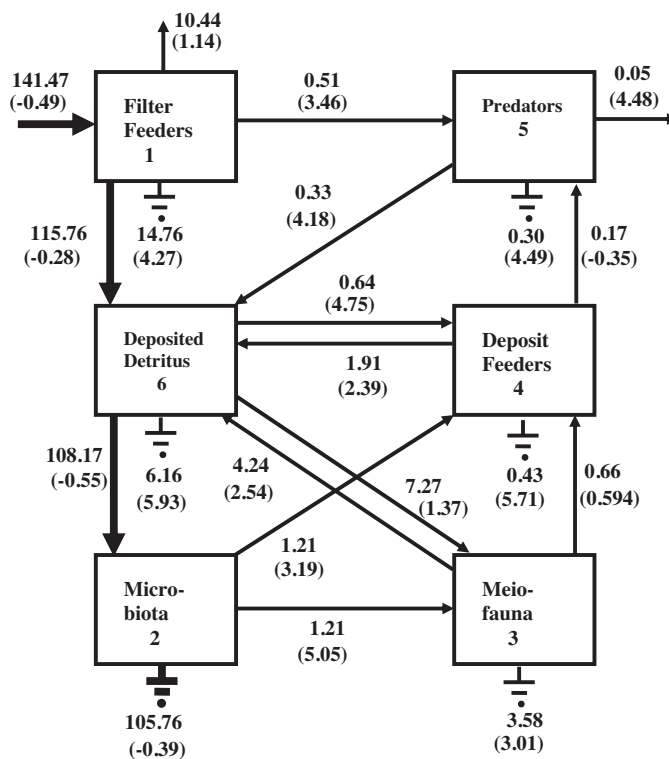
contributions all differ significantly from one. In particular, those flows along the "eutrophic backbone" (the pathway that was amplified) all now have low (in fact, negative) marginal contributions to balance. They would have to be decreased significantly to move the system toward better balance. On the other hand, many of the other flows (mostly among higher components) now make large marginal contributions, indicating that they should be augmented to help balance the system. These relative changes accord well with the measures one would expect must be taken in order to remediate eutrophication. It is significant that remediation in this case requires that one augment the *apophatic* nature of the network – a prescription that would have eluded conventional models. Furthermore, the entire mitigation scenario has been formulated via phenomenology in absence of any knowledge about the detailed dynamics of the system components.

Many ethical mandates are formulated in apophatic fashion (e.g., Thou shall *not* . . .), although positive exhortations (e.g., feed the hungry) are not unusual. Because historical efforts to build a rational, scientific basis for ethics have been predicated largely on positivist notions, the results have been less than satisfactory. A better correspondence between ethics and rationality begs for a science that incorporates both didactic and apophatic elements. We have seen how an enhanced science of ecology accords better with global consensus on environmental action.

9. Misemphasis – a shell game?

The difficulty of reconciling environmentalism with theory is hardly the only problem facing ecosystem science. Many, if not most ecologists remain either critical or disbelieving of the notion that ecological reality is indeterminate. Only a minority seem willing to accept that physics constitutes a necessary but quite insufficient foundation upon which to build a narrative of life. Rather, most ecologists are still preoccupied with trying to build a

mechanistic "hard science" in the 19th Century mold. In all fairness, such desires are not without basis. The laws of physics, after all, remain universal and inviolable. Furthermore, this preoccupation by ecologists is encouraged by physicists themselves. Nobel Laureates, such as Murray Gell-Mann, Stephen Weinberg and David Gross, for example, proclaim that all causality points downward, and that there is nothing "down there" but the laws of physics (Kauffman, 2008).

With such outstanding minds endorsing a reductionist worldview, how can anyone possibly maintain that ecology deals with phenomena that are not fully *determined* (albeit indirectly) by physical laws? In response, I would argue that even the finest minds, following impeccable logic, but proceeding from false absolutes, can arrive at erroneous conclusions. With this possibility in mind, let us look more closely at the fundamental laws of physics (Ulanowicz, 2013).

The universal laws of physics are four in number and correspond to the basic physical forces – strong and weak nuclear, electromagnetic and gravitation. Being universal in application, they can be expressed only in terms of universal variables, such as mass, energy or charge. Those universals in turn must be purely homogeneous properties (Elsasser, 1981). (By "homogeneous" is meant that one cannot distinguish one element from another. For example, individual electrons cannot be individuated.) Any heterogeneity or other particular that applies to the object or situation at hand must be relegated to what is known as the accompanying "boundary statement".

It is unfortunate that investigators rarely emphasize that the full statement of any problem consists of two elements: The first, and what is almost exclusively emphasized, is the universal law or a set of laws that constrains the behavior of a given system within a particular space and over a given time. The formulation of the problem remains incomplete, however, until the investigator makes a necessary set of accompanying statements about relevant circumstances that exist at the spatial boundary and/or at the start. These necessary statements constitute what is called the boundary value problem. Thus it is that one cannot calculate the trajectory of a cannon ball using Newton's second law of motion in the presence of gravity without first stipulating the location of the cannon, the muzzle velocity and the angle of the cannon with respect to the earth. I remark here that it is common among ecological modelers to refer to these boundary specifications as "driving" the model dynamics.

The nature of boundary specifications could not be more radically different from that of the laws in the sense that these stipulations must in general be absolutely arbitrary. Arbitrariness is a necessity, because if one could identify any conditions to which the laws could not conform, then the laws would no longer be universal. Truly universal laws cannot apply just under some conditions and not under others. With attention now fixed upon the necessity of the contingent, we now seek to describe the full range of phenomena that legitimately may qualify as "contingencies".

Perhaps the major reason why boundary conditions are usually glossed over is that the specifications are implicitly assumed to be anything that an investigator *chooses* them to be. (It is important to note here that this interjection of observer choice lends implicit and necessary legitimacy to intentionality as a form of natural contingency.) In the statement of most problems, the investigator chooses boundary constraints that are of a regular and ordered nature. These are the low-lying fruit that we retain as exemplars. Nothing, however, can prohibit boundary conditions that involve chance.

By "chance" one commonly understands random events that are simple, directionless, indistinguishable and repeatable. But these several requirements apply to only a very small subset of all chance phenomena. For example, in complex systems combined actions of multiple simple chance events may constitute a compound event. Such combinations need not be, and usually are not, directionless. Furthermore, physicist Walter Elsasser has argued that combined chance events are usually unique. For example, whenever more than about 80 distinguishable elements or chance events combine, the resulting amalgamation may be considered unique, for it would take an interval more than a million times the age of the universe before that particular combination could be expected to occur again randomly (Elsasser, 1969). I have called such unique chance events "radical", and they fully pervade the complex systems of ecology and the social sciences where the number of distinguishable actors usually exceeds several hundred (Ulanowicz, 2009a,b).

Regarding false absolutes, it appears that Monod's strict dichotomy between chance and necessity is not possible. In between blind chance and strict determinism lies a continuum of events characterized by the degree to which the arbitrary is constrained by the order with which it is fused. At one end of this spectrum, blind, unconstrained chance occurs in a directionless environment. Once there are constraints of any sort, however, (like the imbalance of loaded dice) the resulting conditional probabilities will differ from those calculated for blind chance (Depew, 2011). Going even further, Popper (1990) in his last book, *A World of Propensities*, pointed out how conditional probabilities can grow progressively so constrained that a few outcomes dominate, although occasionally other "interferences" might still occur. Popper labeled such dominant outcomes "propensities", and stressed how they are more general than laws, which he considered to be determinate only in a vacuum or under artificial conditions. Whence, it is possible to describe an entire spectrum of phenomena that legitimately can be classified as contingencies – starting with radical, novel chance, and running the gamut from blind chance to conditional chance to propensities and even to intentionalities.

Important to our understanding of ecosystem dynamics is that contingencies of various sorts can link up in autocatalytic fashion so as to mutually sustain one another (Ulanowicz, 1997). Once thus related, these configurations can endure for quite some time, affecting (and effecting) subsequent events in their course. In this manner, such configurations assume the primary explanatory role behind system behavior, and universal laws, while inviolate and distantly necessary, usually disappear from the narrative. The conventional belief is that the universal laws, though now cryptic, nonetheless project their effects upwards to determine events at higher levels. But such extended linkage is not the only way to imagine the role of laws.

Rather, in my opinion, the real nature of ecological dynamics is best illumined by way of metaphor. It happens, perhaps by accident, that a very apt metaphor for evolution was suggested by physicist Wheeler (1980), who compared the development of science to a parlor game played by guests at a party. The guests elect to play the game "20 Questions", the object of which is to guess a word. In Wheeler's version, one individual is sent out of the room, while those who remain are to choose a particular word. It is explained to the person leaving the room that, upon returning, he/she will question each of the group in turn and the responses must take the form of a simple, unadorned "yes" or "no", until the questioner guesses the word. After the delegated player leaves, one of the remaining players 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 whimsy. 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 contradict either of the first two answers, and so forth. The game ends when the subject asks, "Is the word XXXXX?" and the only response consistent with all previous replies is "Yes".

What immediately strikes one about Wheeler's metaphor is the indeterminate nature of the outcome (Cohen, 1976). The parallels with development and evolution, however, go even deeper. Of especial interest are the rules of the game, which here correspond to the laws of nature. One sees immediately that the rules of the parlor game do *not* a priori determine the endpoint. They guide and constrain activity (presuming that the participants abide strictly by them), but they are *incapable by themselves* of specifying the outcome (Ulanowicz, 2013; Longo et al., 2012). What actually determines the outcome is a *conversation* (dialectic) between the questioner and the respondents. The questioner continuously tries to narrow down the possibilities, much like the action of autocatalytic selection. Conversely, the respondents attempt to keep the range of possibilities as broad as possible, much like the effects of entropic disturbances. I note that combinatorics preclude any effort to fully implement any such conversation in algorithmic form.

As the last statement hints, the core problem with the belief that "laws determine all" is the implicit assumption that it is always possible to state the conjugate boundary constraints. As we have seen, those driving specifications are always contingent to one extent or another and often are indeterminate in nature. When heterogeneous variables come into play (as they invariably do in ecology), the boundary constraints grow completely intractable by virtue of combinatorics (Elsasser, 1969). Under evolutionary scenarios, statement of the boundary problem becomes outright impossible, because the categories necessary for their articulation become apparent only *after* they emerge from ongoing dynamics (Kauffman, 2008).

One concludes that the reversible laws of physics guide but never of themselves *determine* ecological dynamics. Rather, outcomes are the result of the interaction between opposing sets of contingencies. On one hand are the autocatalytic relationships that arise through mutually reinforcing contingencies, build constraints, and maximize power. That drive is opposed by entropic, chance, irreversible, equitable and inefficient contingencies that degrade constraints. It is contingencies, not physical laws, that have initiated *all* patterns of form and activities that we encounter.[8]

10. The way forward

We now recognize our preoccupation with physics as a chimera that has led us astray of ecological reality. While some might despair at the eclipse of the role of universal law in ecology, they instead should take heart in the freedom and enormous opportunity afforded by Kauffman's "end of the era of physics". For, as ecologists we are hardly left orphans.

Patten has rendered ecology a major service with his important and challenging questions. In asking whether we have the science right, he has cast a spotlight on the inadequacies of conventional dynamical theory. Not only is mechanistic reductionism not up to the task of forecasting behaviors of complex ecological systems, but it is also incapable of explicating and/or supporting the full suite of normative attitudes toward the environment. His doubts help to pave the way for the introduction of a more encompassing quantification of reality that is typified by the very networks with which he has spent most of his career.

So it is that the study of networks now appears as the brightest prospect for hedging our bets about the futures of particular ecosystems (as was suggested by the example of eutrophication in the oyster reef community [Figs. 5 and 6]). Challenging work remains to be done by young ecologists to illumine better the Heraclitian transaction between building ecosystems up and tearing them down. I hope by now the reader is convinced that indeed we did not get conventional science right. By balancing the didactic against the apophatic, however, we now possess a richer, deeper narrative of the evolution of ecosystems that finally casts real light on a colorful *living* world.

As ecologists, our discipline has always been considered a vassal of the "hard sciences", so that we have remained dependent upon advances in other fields for our own development. However, as Odum (1977) once predicted, the bottom rail is now on the top, and we find ourselves at the forefront of scientific progress – able, better than those in most other fields, to formulate new and pioneering schema for how life arose, acts and will develop.

Acknowledgements

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[8] Almost the same scenario for evolution was espoused by Gould (1990), the significant difference being that he limited the guiding role in evolution to blind, directionless chance.

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