Two Frameworks for Complexity Generation in Biological Systems

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Abstract

Two hierarchical frameworks for complexity generation in natural systems are described, as (a) a synchronic system, extensional complexity, of wholes and parts, with the levels having dynamics separated by about an order of magnitude, and (b) a diachronic system, intensional complexity, with each higher level entraining all lower ones. Complexity is generated in both as a result of perturbations. generated by historical fluctuations. I see complexity as the problem of nonpredictability of systems even when using 'true' models of them.

This paper takes a more general systems, rather than a detailed technical stance on complexity. From the point of view of science, complexity is recognized by the failure of dynamical determinism. I will suggest two sources for this that can be made apparent by way of hierarchy theory (Salthe, 2002). We have (a) the fact that systems of different scale affect each other without directly interacting as a result of existing at the same locale, and (b) the fact that natural systems are susceptible to multiple kinds of influences. In both cases the result is interference with trajectories and configurations predicted from rational models. If the world were strictly logically based, our models, no matter how complicated, would, like Laplacean Demons, give accurate and sufficiently precise predictions. But material nature seems to guarantee rampant contingency, and that parlays to perturbation by the intrusion of fluctuations. Complexity is invoked by perplexity which, I suggest, is provoked by effects of the simultaneous presence of multiple levels -- and kinds of levels -- of organization.

Two General Frameworks for Complexity Found in Biology, and elsewhere.

(a) The *extensional complexity* framework, modeled by the scale hierarchy (Allen & Starr 1982, Salthe 1985), as in the nested hierarchy: [biome [population [organism [cell [macromolecule]]]]], which is interpreted as [higher level [lower level]]. Note as well, [rare event [uncommon events [common events]]]. So square brackets. [ ], signify both physical enclosure and differences in rates of change, with slower rates entraining faster ones.

Dynamical rates at the different levels in a scale hierarchy are separated by about an order of magnitude (Salthe 2004), thereby preventing direct dynamical interaction between levels in favor of indirect constraint imposition across levels. This essentially synchronic structure, modeling a situation at a given moment, has been viewed as the most stable configuration for the simultaneous co-occurence of systems of many different sizes (Simon 1962, Kolasa 2005), and one that maximizes overall entropy production as well (Salthe 2004). A triadic structure: [contextual boundary conditions [focal dynamics [initiating possibilities]]] is canonical and primordial for this system, which cannot be derived from unconstrained bottom - up processes. New levels are interpolated between preexisting ones (Salthe 1985, 2004).

Complex (e.g., chaotic) dynamics are here generated at a given level by changes in constraint relations between levels, these being triggered in lower levels by fluctuations in the higher levels, which result in altered boundary conditions being imposed upon the lower levels. Also, as each level blocks direct downward transition of signals from higher levels by stopping or transducing -- thereby moderating -- them, when this fails lower levels experience disruptions that also generate complex dynamics. So here complex dynamics result from the structure of the system

(b) The *intensional complexity* framework (Sabelli and Carlson-Sabelli 1989, Salthe, 1991, Rosen 2000), is modeled by the specification hierarchy of realms of Nature (Salthe 1993) as in {physical reality {material realm {biological realm}}}, which is interpreted as {lower level {emergent higher level}}. The levels here are modeled as classes and subclasses, as in set theory. Thus, biology is a kind of chemistry, which, in turn, is one kind of physical system.

This implicitly diachronic form is generated by way of the bottom - up emergence of new, more highly constrained, realms out of more generally present prior ones during development, as in, {physical processes -> {material connections -> {biological form}}}. Taken as a process model, the lower levels are seen to be continually supporting upper levels in a 'present tense' manner. Development of new levels is afforded proximally by a continued production of informational constraints during system growth, and ultimately as a result of the creation of matter afforded by the accelerated expansion of the universe in the Big Bang. At any given moment in a biological system, physical processes are supporting the material framework, which affords the continuance of biological activities.

Fluctuations during emergence of a realm will create mutations. In biology this occurs importantly during ontogeny, e.g., {living -> {animal -> {amphibian -> {frog -> {leopard frog}}}}}, with surviving mutants being possible after the phylotypic stage (Hall and Olson 2003).

Biology is a realm where some of the results of historical fluctuations can been preserved as altered mutants, which have cumulated to the different lineages of biological diversity, and this diversity, locally or globally, is the source of the complexity this system generates, as informational entropy at any given locale. Locally, the greater the diversity (and therefore variety of possible interactions), the less predictable any next configuration will be for either a participant or an observer. Globally, the greater the diversity, the more adjacent possible futures are available for system occupation via evolution, and the less predictable they will be. So here complexity is disorder generated by the organization of the system.

Extensional and intensional complexities can be related to each other from the point of view of an individual observer as shown in Figure 1.

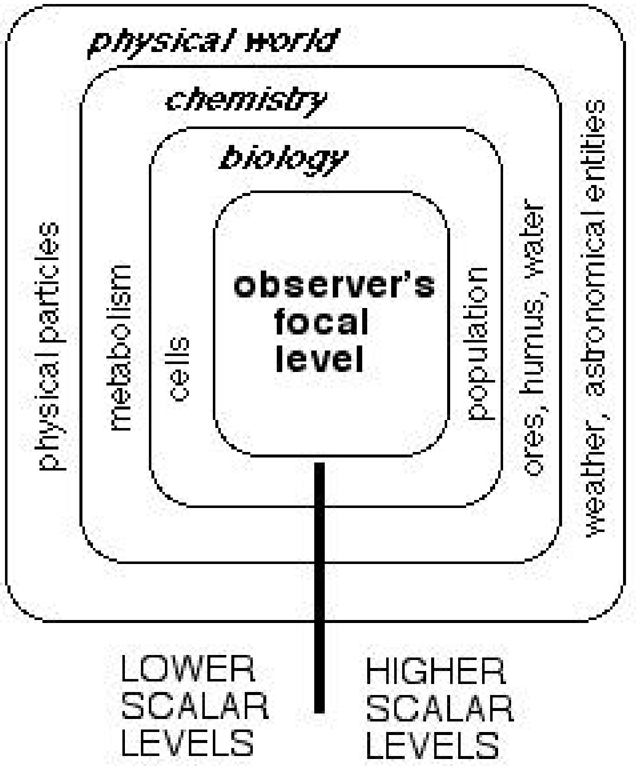

Figure 1. Modified from Salthe, 1985.

This figure can be taken as a mandala, suggesting the relationship between the scalar levels of extensional complexity and the integrative levels of intensional complexity. The observer arises out of the physical - chemical and biological realms as the peak of pyramid rising from the left, but at the same time is embedded in these containing realms as a trough dipping in from the right.

Addressing Gershenson's Questions from these Two Hierarchical Perspectives

(1) With regard to "What are the environmental constraints of complexity growth in living systems?" [note that under the (a) headings I give replies from the extensional complexity perspective,

and under (b) headings from the intensional complexity perspective, based on my general summaries of these perspectives in Salthe, 1985, 1991, 1993, 2002: My answers will address complex systems generally rather than living systems in particular except where noted.

(a) Ultimately, complexity growth here would have been produced by the generation of gravitation during Universal expansion in the Big Bang, with resulting masses of different sizes, thus: universal cooling -> precipitation of matter -> gravitation -> masses. With this we have had the addition of information into the system. System complexity growth here occurs consequent upon the interpolation of new dynamical levels between existing ones. This curtails the growth of complication and consequent dynamical friction at existing levels in favor of increasing the overall complexity possibilities of the system, as afforded by the opportunity for increasing its overall rate of entropy production (Salthe 2004).

(b) Basically, complexity growth here is driven by system expansion or growth, affording the refinement of existing information by the imposition of newly added constraints. Thus: {physical -> {material -> {biological -> {sociopolitical}}}}, by way of the historical pattern: precipitation of matter -> gravitation -> selection -> intentional action. So, here we have a modulation of prior information by newly added information, delivering further organization of prior existing forms into new collective properties. Thus, in both hierarchical complexity increase requires systems expansion or growth, which needs to be afforded by the environmental surrounds.

(2) “Are the principles of natural selection, as they are currently understood, sufficient to explain the evolution of complexity?"

No. In neither (a) nor (b) is selection an important feature in the generation of complexity, although it does play a role in what survives -- in the later stages in (b). Selection is a process that decreases the number of types in a population, reducing its informational entropy (Brooks and Wiley 1988), irrespective of population growth, which is governed separately by environmental affordances (Wallace, 1970)..

(3) “What are the limits at different levels to the evolution of complexity?"

In these systems complexity ‘evolves’ by way of creating more opportunities for the imposition of fluctuations.

(a) As already noted, if the opportunity to increase entropy production arises in the overall system context by way of creating more levels, that will occur preferentially to increases of complication at any particular already existing level(s). If, instead, complication increase occurs at the separate levels, then the opportunities for cross level perturbation in the system will not increase.

(b) Here the complexity of importance is generated at the highest instantiated level relevant to a given viewpoint. The appearance of slaving constraints (Haken 1988) in that level will increase a system’s overall complexity generating ability during the emergence from it of a new higher level based on those slaving constraints. If no such constraints arise, the complexity generating framework cannot increase.

(4) “Which conditions could reduce evolved complexity?”

Basically, in both (a) and (b), it would be conditions curtailing system expansion or energy throughput.

(a) Increase of complexity generating ability at a given level may be limited by opportunities to increase global entropy production instead, by interpolating a new level between it an adjacent one, thereby increasing the overall complexity possibilities. Curtailed system expansion or growth, or energy limitation, would restrain evolution of the extensional complexity framework. Severe energy limitation could result in collapse of the system to fewer levels, losing levels from the middle scales.

(b) In this system the number of levels affords the overall complexity possibilities. The appearance of slaving constraints (Haken 1988) could give rise to a new higher level, which then takes over some of the complexity generation, and increases overall complexity generativity at the lower levels. Limits on the reach or span of slaving constraints would prevent overall system growth in intensional complexity. Unlike in (a), where constraint moves stepwise from level to level, here constraint reaches down through the hierarchy in transitive fashion. For example, biology directly entrains not only chemistry but physical processes like diffusion as well. Therefore, loss of a top level will reduce the number of constraints bearing upon all lower levels, reducing their number of possible collective configurations.

(5) "Which models are / what language is more appropriate to understand / speak about the evolution of complexity in living systems?"

Either of (a) or (b) could be appropriate models, depending upon observer perspective. Both of them concern the emergence of 'new levels' from 'lower level' potentialities.

(a) is concerned with scalar levels: e.g., [species [population [organism [cell[macromolecule]]]]] -- i.e., with extensional complexity. Increase in extensional complexity involves cohesion of smaller scale entities into larger scale ones (Collier 1988), as afforded by (or permitted by) constraints imposed by a pre-existing even larger scale encompassing system (Salthe 1985).

(b) is concerned with intensional complexity, as in the integrative levels: {physical process {chemical recognition {biological form}}}. Increase in intensional complexity involves reorganization of lower level entities into new collective forms under control of emergent slaving rules, Haken (1988), Salthe, (1993)..

(6) "How could complexity growth be measured or operationalized in natural and artificial systems?"

In either (a) or (b), we would seek the emergence of stable new collective forms. In (a), these would be new associations involving fewer previous lower scale units in each, by imposing a quantitative increase in barriers to their direct interaction. In (b) these would be re-alignments of previous units into newly stable collective forms that were previously immanent as vaguer or more episodic associations; this is an increase in qualitatively new kinds of forms, entities or systems.

(7) "How can data from nature be brought to bear on the study of this issue?"

For example, in studies of ontogenetic development.

(a) Changes in extensional complexity occur naturally in cellular slime molds -- the motions of individual amoeboid cells becoming entrained into the motion of a larger aggregate, forming a larger scale migrating 'slug' (Bonner 2000).

(b) Developmental emergences resulting from individual cells migrating and accumulating into new forms after which they differentiate, as with the neural crest cells of vertebrate embryos forming many different tissues in different locales (Hall 1999). The specification hierarchy of integrative levels is formally a tree (Salthe, 1993), and this example is neatly modeled using it, with the generative neural crest cell in the trunk.

(8) "What are the main hypotheses about complexity growth that can actually be tested?"

Changes in the disposition of prior entities are brought about by their being exposed to, and harnessed by, new global constraints

In (a) this would be brought about by making it possible for the overall system to increase its entropy production. This quantitative change would be elicited from outside by an affordance for system expansion, or by regulating energy throughput.

In (b) this would be brought about by encouraging the spontaneous emergence of slaving rules. The experiment would need to be arranged so that the qualitative change comes from within the system, either developmentally and/or via receptivity to internal fluctuations (Salthe 2005). So it would involve designing the basic units very carefully.

(9) "Is it possible to direct / manipulate the evolution of complexity?"

This might be discovered during the explorations suggested just above under the question of testability in (8). In (a) manipulation of boundary conditions would be the basic technique. In (b) construction of the subjects of the experiment would have to be very carefully engineered so that configurations that they themselves might access could lead them to construct new stable alignments.

(10) "Which benefits would bring its understanding?"

Only by understanding these questions in the contexts I have suggested will it be possible to learn how to engineer self-organization. Currently the understanding of the nature of differences (in scale and kind) between levels in natural examples of hierarchies seems to be underappreciated.

Conclusions

In order to sharply focus the logic of these hierarchies, we can use the general equation: $Y = aX^b$. In the extensional complexity framework this can be decomposed as: [a, b [X, Y]], and, in more detail, [a [b [X]]], showing that b regulates or contextualizes X, while a, at a still higher level, controls b. At the same time, X provides the value that will be controlled by b. It is clear that any fluctuations in the contextual values, a or b, will cause dramatic changes in the output of the equation. In the intensional complexity framework, we can deconstruct the equation as: $\{ Y = (f) X \rightarrow \{ Y = X^b \rightarrow \{ Y = aX^b \}\}\}$, gradually refining the information regulating X, as if the system containing X were developing. Fluctuations during the emergence of a or b will deliver large changes to the output of the equation.

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