

MARK H. BICKHARD and DONALD T. CAMPBELL\*

VARIATIONS IN VARIATION AND SELECTION:  
THE UBIQUITY OF THE  
VARIATION-AND-SELECTIVE-RETENTION RATCHET IN  
EMERGENT ORGANIZATIONAL COMPLEXITY

**ABSTRACT.** The variation and selection form of explanation can be prescinded from the evolutionary biology home ground in which it was discovered and for which it has been most developed. When this is done, variation and selection explanations are found to have potential application to a wide range of phenomena, far beyond the classical biological ground and the contemporary extensions into epistemological domains. It appears as the form of explanation most suited to phenomena of *fit*. It is also found to participate in multiple interesting relationships with other forms of explanation. We proceed with an examination of multiple kinds of phenomena, interrelationships with other members of the family of forms of explanation, and some novel applications even within the home ground of evolutionary biology.

**KEY WORDS:** evolutionary biology, evolutionary epistemology, explanation, variation and selection

Variation and selective retention is the paradigm form of explanation for adaptedness in evolutionary biology. This form of explanation has also been extended to several other domains, including scientific thought itself. The basic thesis of this paper is that there are many forms of explanation, each appropriate to particular kinds of explanation sought, and that variation and selection is a general form of explanation that is appropriate for explaining *fit*: that *all* regularized forms of satisfaction between the dynamics of systems and some criterion of “fit” for those dynamics are, in general, best explicable

---

\* Don died May 6, 1996, from complications after surgery. He was a genius whose heart was even larger than his intellect; he was a friend and a mensch. This paper had undergone growth by the addition of references and arguments over the course of several years. The first author has completed it after Don could no longer contribute (and object!) with as little further change as was compatible with already anticipated but not yet completed additions.



*Foundations of Science* 8: 215–282, 2003.  
© 2003 Kluwer Academic Publishers. Printed in the Netherlands.

in terms of some form of variation and selection process (Campbell, 1974a, 1987, 1988a, b). In some cases, the paradigm cases, this basic point seems obvious, but in others, not so obvious. Furthermore, the extensions of the thesis into realms that are distant from the home realm of variation and selection in evolutionary biology yields interesting shifts in perspective on some phenomena, and on properties of explanation itself. The discussion will proceed via illustrations both of various kinds and domains of phenomena, and of various relationships of variation and selection explanations with other forms of explanation.

By now, wherever there is a working consensus that an innate aspect of any organismic form is adapted to environmental opportunity, there is apt also to be a consensus that it is a product of unforesighted recombination and mutation of genes, selectively retained and reproduced: the typical exemplar of the “variation-and-selective-retention” ratchet. Among immunologists, there is almost as solid a consensus that the Jerne-Burnet model of acquired immunity is correct: a proliferation of possible antigens, with a selective retention and reproduction of those that deactivate the toxin (Burnet, 1959; Jerne, 1967). Well argued, although with less consensus, is the case that all learning not involving vision can be subsumed under an unforesighted trial-and-error model. Long-standing arguments going back to Bain, Jevons, James, Mach, and Poincarè extend the model to creative thought, an insight still being repeatedly reinvented although no consensus can be claimed. Still less consensual, there are explicit variation-and-selection models that lump echolocation, sonar, radar, and vision together; and a subspecies of evolutionary epistemology and cultural evolution which looks to non-prescient variation and selective retention in science.

All of these we can classify as models of “external” selection. All are examples of the “adaptation” resulting in the “fit” of one system to the stable aspects of its environment. While the degree of consensus on these exemplars varies, all have been sufficiently well argued for the present purposes.

This paper seeks, among other things, to call attention to the ubiquitous presence of such a ratchet (whether external or internal) in processes of self-organization, autopoiesis, autocatalysis, emergent

higher levels of organization, periodic attractors, strange attractors, and so on: i.e., processes often offered as contradictions to variation and selection based adaptation, and in which the end product is increased organizational complexity rather than fit of adaptation per se. In most of this literature, as applied to biology, even if neo-Darwinian processes are allowed, where increasing complexity emerges the neo-Darwinian processes are relegated to selecting among self-organized forms whose emergence variation and selection cannot explain.<sup>1</sup> By stressing the ubiquity of the variation-and-selective-retention ratchet in self-organizing processes, we hope to reduce this appearance of conflict.

As the initial superhot plasma of the big bang cooled, stable combinations of the most elementary particles emerged – hadrons, atoms, molecules, and so on. We also want to call attention to how even the physics of these transitions can be mapped onto the variation-and-selective-retention ratchet. In the “crystallization” of hydrogen atoms out of the plasma, as in the crystallization of salt crystals in a saturated salt solution in our kitchen, the critical role of temperature, and the staging by “cooling” is observed. Variation and selective-retention are at odds: too much variation (too high a temperature) and there is no retention of the atomic-level adjacencies in the crystal surface. Too little variation (temperature at absolute zero) and there is no opportunity for an emergent order to be created. In the intermediate zone (on the “edge of chaos” as the chaos-and-complexity theorists phrase it), emergent order can occur, as through selection from the chancy exploration of the stability-possibilities of the sub-level particle adjacencies.

#### EXPLANATION

*Efficient causality and dispositions.* There are many forms of explanation. In the positivist heritage in which most of us live, the paradigm form of explanation is *efficient causality*. Efficient causality is an appropriate kind of explanation, for example, in understanding why this billiard ball is traveling with that velocity vector – it was hit by this other billiard ball, and so on. Efficient causality, however, is not an appropriate form of explanation if we ask why it is that billiard balls react that way to being struck, while balls of

putty, for example, do not. Such a question requires a *dispositional* form of explanation in terms of the elasticity of collisions of billiard balls, and the inelasticity in the case of balls of putty.

*Initial and boundary conditions.* Another form of explanation is *initial condition* explanation. In this case, why a given state of affairs is so is explained in terms of what its initial-condition state of affairs was, and the ensuing development occurring in accordance with whatever laws of dynamics are appropriate. A related form of explanation is *boundary condition* explanation. Here, the critical explanatory considerations are not (only) initial conditions with which a process begins, but the boundary conditions within which the process proceeds. Understanding the development of turbulence over and behind a wing, for example, will require reference to the shape of the airfoil as a boundary condition within which the air flow develops. Insofar as birth order is explanatory of personality characteristics, it forms a boundary condition within which other personality formative processes take place.

*Teleological, variation and selection, and intrinsic explanations.* Still another form is *teleological* explanation, in which goals or purposes are necessarily involved. Such explanations, clearly, require the involvement of some agent that is capable of goals or purposes. Two forms of explanation that we will focus on are *variation and selection* explanations and *intrinsic* explanations.

*Explanations of explanations.* Differing phenomena, and differing questions about phenomena, require appropriate forms of explanation, and explanations themselves are subject to explanation – generally of a form different from the form of the explanation being explained. In the billiard ball example, events such as the billiard ball traveling in such and such a way are explicable in terms of other events – being struck – but only in the context of the disposition toward elastic collisions that relates events of being struck to events of moving with certain velocities. Such dispositions, in turn, may be explained in terms of properties of electron shells, and so on.

*Discovering new forms of explanation.* Variation and selection is a particularly powerful form of explanation, both of phenomena

directly and of other forms of explanation. It also illustrates that new forms of explanation are, from time to time, discovered – by Darwin, in this case.

#### VARIATION AND SELECTION EXPLAINS SATISFACTION RELATIONSHIPS

We will illustrate the involvement of variation and selection processes and perspectives in phenomena at several levels and explanations of several forms. Variation and selection is particularly apt, and apt to be necessary, whenever a process that is otherwise unconstrained in fact satisfies some constraint. In general, such satisfaction is explained in terms of the satisfied constraint serving as a selection principle on the process in question. In fact, it is arguable that such processes of selection are logically necessary to explain most relationships of satisfaction of constraints by processes. This point includes constraints both of regularity of process and of stability of organization of process. The basic point is that, without the operation of selection on a process, the process can satisfy a constraint in only three other ways: (1) with random fortuitousness, (2) with prior guidance toward the satisfaction of the constraint, and (3) with prior adjustment, or “aiming”, of the process toward the satisfaction of the constraint. Prior adjustment of the process, however – preformationism of the process – is just a form of prior guidance; thus 3 collapses into 2. Prior guidance, in turn, is itself either entirely fortuitous, or is itself a product of prior selections.

The only two possibilities, then, are fortuitousness or variation and selection. Fortuitousness, however – accident – is little explanation at all, and is ultimately acceptable only if there are in fact good grounds for ruling out conceivable alternative explanations. Such grounds can be inherent in the nature of the process itself (such as, perhaps, with the collapse of a wave function in quantum mechanics) or inherent in the irrelevance of whatever constraints do apply (such as in the fortuitous skipping of a tornado over one building while destroying everything around it).

*Instances* of satisfaction, then, may in some cases be legitimately explained as fortuitous, but almost never can *regularities* of satisfaction be legitimately explained via fortuitousness.<sup>2</sup> Variation and

selection is the form of explanation *par excellence* for satisfaction phenomena – for *fit* (Campbell, 1988a, b).

This point is nowadays “obvious” for fits or satisfactions in biological evolution, and has been extended to many other phenomena, especially those involving something akin to knowledge or information (evolutionary epistemology, philosophy of science, and so on; Campbell, 1959, 1974a, 1990a; Cziko, 1995; Hahlweg and Hooker, 1989; Radnitzky and Bartley, 1987). We will argue that the appropriateness of variation and selection extends beyond these more familiar instances.

Understanding the broad appropriateness of variation and selection forms of explanation requires understanding a strong distinction between variation and selection as a process involved in biological evolution and variation and selection as a more general form of explanation. If employed strictly as a property of evolution, variation and selection may be invoked in various ways via stronger and weaker *analogies* to evolution. Such explanatory invocations depend on the strength of the analogies involved, and are limited in scope to domains in which plausible such analogies can be constructed.

Variation and selection as an abstract form of explanation, however, prescind from the evolutionary domain in which it was discovered (Campbell, 1988b). As a form of explanation, variation and selection is arguably a necessary form of explanation for any regularities of satisfaction of some criterion by an otherwise unconstrained system or process – as in the discussion above. In this view, biological evolution is an instance or an application of the more abstract form of explanation.<sup>3</sup> Evolution, in this view, is only incidentally the source of inspiration, not a source of rational plausibility for variation and selection models via analogical bridges. Failures of details of such analogies to biological evolution (e.g., failures of analogy to genotype and phenotype distinctions) become irrelevant if variation and selection is a form of explanation that already transcends evolution.

#### *Energy-well Stabilities; Formation and Persistence*

Many stabilities of the organization of process are (potential) energy-well stabilities – stable organizations of process that are stable because it would require more energy than is available to alter

the organization of the process. Atoms, molecules, rocks, planets, stars, and galaxies are representative kinds of energy-well stabilities. We will argue that energy-well stabilities exhibit variation and selection phenomena both in their formation and in their stability once formed.

*Crystal growth.* Consider, for example, the growth of a crystal from material in solution (Campbell, 1974b). The atoms or molecules in solution are in thermal and convective motion that changes their positions and orientations in a manner that is blind to the potentialities of crystal formation. The crystal already formed provides *absorbing conditions* for those atoms or molecules in solution in the sense that any atom or molecule that happens to enter the “right” position and orientation will be absorbed into the surface of the crystal with a release of kinetic energy, and a consequent energy-well stability of the resultant addition to the crystal. The absorbing conditions on the surface of the crystal act as selectors on the otherwise relatively random motions of the molecules in solution.<sup>4</sup>

*Absorbing conditions.* Absorbing conditions are a general form of selection that accounts for a number of emergences of some sort of order out of prior disordered process. A trivial example is the tendency for gravel on a road to end up on the edges: no particular movement of the gravel need have any bias toward the edges, but any resting place other than the edges is unstable because of the introduction of high energy from passing tires. The road edges are the “energy-well” stabilities in the sense that further movement requires energy that simply isn’t delivered to those edges. In this “absence of energy in the absorbing conditions” property, the road edges are akin to the energy-well stability of crystal formation: the thermal energy released by the absorption (e.g., molecule entering crystal or gravel striking the road) is taken up elsewhere (e.g., by the solution or road or the air), and the energy that remains is insufficient to move the atoms or molecules or pieces of gravel out of those conditions.

In Markov Chain terms, absorbing conditions are those for which there is a non-zero probability of transition into those states, but zero probability of transition out. Note that, so long as the transition probability into an absorbing state is non-zero, then the state is certain to ultimately end up in that condition no matter how small that

transition probability might be. (The existence of other absorbing conditions, or absorbing regions of the state space, may render the transition probability into a particular absorbing state zero if the system enters one of those other absorbing regions of the space.)

*Crystal stability.* Once a crystal is formed, the atoms or molecules still engage in thermal motion. Again, however, the energy-well acts as a constraint on those motions, holding the crystal together. If an atom or molecule receives enough energy in the course of the random jostling within the crystal, it may succeed in leaving the crystal. In crystal formation, in fact, such random loss is always occurring, and formation results because the rate of deposition exceeds the rate of loss. In the case of gravel on the road edge, similar thermal motion occurs, but it would be *exceedingly* rare for such random thermal energy to suffice to jostle a piece of gravel back onto the middle of the road: the ambient temperatures involved are simply too low relative to the energies required to move a small rock. Since the energies involved in processes of crystal formation are closer to available thermal energies, release from a crystal surface is a much more common phenomenon than “thermal return of a piece of gravel”.

*Atoms and molecules.* The formation of an atom out of hadrons, or a molecule out of atoms, is similar to crystal formation in that the absorbing conditions of process organization – of electron waves relative to the nuclei – constitute energy-well selections. Thus, otherwise random motions of the constituents can end up in stable organizational configurations of atoms or molecules by virtue of falling into those absorbing conditions.

*Catalysis.* An interesting phenomenon that is related to these considerations is that of catalysis. If a transition form of a molecule, for example, is of higher energy than its otherwise stable configuration, but nevertheless can be reached by random thermal motion, the molecule may actually attain that intermediate transition form with reasonable frequency due to thermal fluctuations, only to fall back into the energy-well. If some other molecule is available, however, that can stabilize the molecule in its transition form – by, in effect, scaffolding an extrinsically created energy-well for that transition



form – then the molecule may remain in that transition form for longer periods of time. In that transition energy-well, in turn, the probability of transition into a new configuration entirely, with its own energy-well, that can be quite different than the original energy-well (such as a break up of the molecule, or a recombination among molecules into different ones), can be higher than before, and can have more time to occur than when there is no stabilizing transition energy-well available. Overall, this relative stabilization of an intermediate, transition form will increase the rate of transition from the original configuration to the new one, via the temporary stabilization of intermediate forms – via the temporary selection of intermediate forms as energy-wells themselves. Such stabilizing selections for transition forms is the general manner in which catalysis functions (Lienhard, 1973).

*Energy-well formations and stabilities as variation and selection phenomena.* Thus, we find that energy-well stabilities result, not from inertial fixedness per se, but rather from selective differentiations of rates of change – change, or variation, which is thermally (and uncertainty-principle) guaranteed and ubiquitous. The Aristotelian conception of bodies tending to move to their proper places, and then simply resting there, is not tenable in the view of contemporary physics. Energy-well stabilities clearly involve thermal and quantum variations, upon which are imposed energy-based rate-of-change selections.

#### *Open systems*

*Ontologically necessary openness.* Some organizations of processes exhibit a stability that is not an energy-well stability. These organizations *require* continued transactions with their environments, of energy or material, in order to maintain stability. As such, they require appropriate boundary conditions in those environments for these necessary exchanges to continue. Such organizations are far from equilibrium, open systems (Nicolis and Prigogine, 1977, 1989).

An openness to interchanges with their environments is ontologically necessary for such systems. Without these exchanges, they would otherwise devolve toward equilibrium, which would elim-

inate the crucial system organization. One consequence of this necessary openness is that the boundaries of open systems cannot be defined simply in terms of energy-wells or energy barriers, since any well or barrier that suffices to prevent open exchange would also suffice to eliminate the system itself.

*Convection cells.* A simple example of an open system is an organization of convection cells – Benard cells – in a pan of water heated from below. These cells exhibit and maintain an organization that is dependent on various boundary conditions, such as the shape of the container, the dimensions of the container, the volume of water, and – most importantly – the temperature differential between the bottom and the top of the water. Significant alterations in any of these can change or eliminate the organization. The heat input at the bottom of the container is an essential condition, and the stability of the convection cells requires continuous flow of heat energy from the bottom to the top of the water. It is the necessity, this ontological necessity, for exchange of heat energy that makes even such simple convection cells examples of far from equilibrium, necessarily open, system organizations.

*Emergent organization.* Far from equilibrium open systems can manifest many interesting resultant and emergent properties (Anderson and Stein, 1984; Careri, 1984). The convection cells are themselves an emergent spatial organization out of random thermal processes occurring in the water prior to the establishment of the disequilibrium flow of heat. Many spatial and temporal emergent regularities of organization have been discovered, and life itself is an example of far from equilibrium open system, though of a very special kind (Nicolis and Prigogine, 1977, 1989).

The emergence of such organization in such open systems is itself a result of the emergence of internal mutual constraints on the thermally random activities of the materials involved. It is the emergence and stabilization of these internal process constraints, these *selections* on underlying random processes, that generates the emergent organization of the overall system (Anderson, 1984; Careri, 1984; Nicolis and Prigogine, 1977, 1989; Prigogine, 1980).

*Self-maintaining and Recursively Self-maintaining Systems*

*Self maintenance.* There is a special kind of far from equilibrium system that might be called a *self-maintaining* system. If some of the resultant or emergent properties of an open system tend to maintain necessary “boundary” conditions for the existence of the non-equilibrium system organization – e.g., combustion in a candle flame maintaining above-threshold conditions of temperature, that, in turn, help to maintain the flame – then the persistence of the instance of organization is at least partially explained by that emergent property or properties of the system itself. Self maintaining systems, then, maintain one or more of their own ontologically necessary boundary conditions. Convection cells in heated water, in contrast, do not maintain any of their own necessary boundary conditions.

System conditions will intrinsically tend to oscillate, with a tendency toward thermodynamic equilibrium. In an open system, that tendency is overcome by the continuing exchange with the environment that maintains far from equilibrium conditions. In a self maintaining system, the system processes or organizations themselves yield resultant or emergent conditions that maintain (or contribute to) necessary far from equilibrium conditions. In both cases, state oscillations away from equilibrium are selectively enhanced.

*Recursive self maintenance.* A still more specialized case of a self maintaining system might be called a *recursively* self maintaining system (Bickhard, 1992b, 1993, 1998, 1999; see also Christensen and Bickhard, 2002; Christensen and Hooker, 1998, in press, on autonomy). The key emergent property here is that the system tends to maintain its own property of being self maintaining. Such recursivity requires some sort of consequence, or feedback, of the system’s own success, or lack of success, in self maintenance. Since the system overall either persists or ceases, that feedback cannot be simply of the system’s existence – any negative feedback of that would involve there being no system to receive the feedback. Recursive self maintenance, then, requires feedback of some *surrogate* or *vicariant* for the system’s success at self maintenance (Campbell, 1974a, b, 1988a).

*Adaptivity: Appropriate shifts in self maintaining activity.* The function of such feedback is to control shifts in the process so that various differing kinds or degrees of resultant and emergent properties are produced in order to counter various kinds of possible perturbations of the system organization from the environment. A flame that could change location when fuel was running low at its current location would exhibit a simple form of recursive self maintenance. A living system will exhibit many possible such shifts of internal process in order to accommodate shifts in environmental conditions. Recursive self maintainant systems, then, can adjust self maintenance with respect to variations in environmental conditions; they can shift system activities in accordance with shifts in environmental conditions. They are organized so that environments can select or invoke relatively appropriate forms of system processes. They can adapt.

*Evolutionary improvement.* There are many interesting properties of self maintainant recursivity and its feedbacks. The critical one that we wish to point out here is that *populations of self reproducing* recursively self maintainant systems manifest the emergent possibility of getting better and better at being self maintainant over the course of the generations of self reproduction. Self reproduction will never be exact, and the variations introduced will constitute, among other things, variations in the recursive self maintenance ability of the system types. It will constitute variations in the adaptiveness of the system types.

More adaptive self maintainant systems will, in general, be more successful at self maintenance. If resources are limited, or if environmental conditions are harsh, there will be a tendency for less adapted – less able recursively self maintainant system organizations – to cease and to fail to reproduce. Populations of self-reproducing recursively self maintainant systems, then, will exhibit emergent variation and selection *evolution*.

The selectors in such evolution will be of at least two types: (1) “external” selection by the relatively stable environment of the system. Selection theory has focused almost exclusively on this type. And (2) “internal” selection, such as the requirements of organizational stability and systematicity. We examine such distinctions among types of selection below.

*Evolutionary historicity.* Many internal constraints and forms of selection will emerge in the course of biological evolution: genotypic-phenotypic relationships; species and speciations; various sorts of embryological and biochemical entrenchments; the emergence of sexuality; the emergence of sociality, communication, and culture. All of these satisfy some selection constraints, offer new adaptednesses, encounter new forms of selection, and manifest new selections on and opportunities for other individuals and species. In this manner, evolution involves a high degree of evolving internal constraint, and the internal emergence of new potentialities for adaptedness. In being in these senses intrinsically internally driven, biological evolution is *ipso facto* intrinsically historicistic: its conditions at any given point are not fully determined by its external boundary conditions, but are in large part determined by its own internal conditions that result from its own history. In other words, the intrinsic historicity of evolution is itself an ontological emergent of the nature of evolution.

One general version of such historicity is the phenomenon of system types that might be otherwise rare or absent becoming instead common and frequent – by virtue of the random coming-into-existence of an initial instance followed by auto-catalytic or self-reproducing proliferation of further instances. In such a manner, a-priori low probability systems can come to manifest factual high frequency – the auto-catalytic or self-reproducing properties of the systems drastically alter the probabilities of further instances being created.

Canonical domains of variation and selection explanation have involved such explanations of “frequency where we might expect rarity” or “presence where we might expect absence”. Life per se, of course, is the paradigmatic example, with all of its varieties being specific examples. This application of variation and selection forms of explanation makes use of the historicities involved in reproduction in addition to the basic variation and selection processes. In contrast, crystal formation and its many absorbing condition relatives show that variation and selection explanations can also be involved where historicities of these autocatalytic or self-reproducing kinds are absent or relatively minimal.

Even here such historicities may not be entirely absent. It is, for example, much more difficult for a crystallization to occur, or con-

densation, or many other such processes, if there is no seed crystal, no enhancing initial condition, present. Furthermore, some materials will crystallize in more than one possible structural form, with the form instanced in a particular crystal dependent on the historicity of the boundary condition constraints imposed by the (random) initial seed crystal.

Conversely, given the specifics of some class of molecules, the possible forms of stability in, for example, crystal formation, are determined, predictable (in principle), and relatively few in number. At the level of the formation of atoms, hydrogen and helium were “independently invented”, or “discovered”, as absorbing conditions all over the cooling universe, and similarly for carbon, iron, and other elements in stars and nova. In such cases, we find a relative predictability of the possibilities for emergent macro-order from knowledge about lower forms of order.

In contrast, the space of possible forms of *organism* is vast, and is *not* determined by properties of constituents – and is certainly not synchronically predictable. In cases such as the latter, historicity considerations provide our only explanation of why any such system exists at all, and certainly of explanations of why those particular forms of system exist. In the former types of case, however, historicity plays a smaller role, and its role disappears, for example, when there is only one possible crystal structure.

But the role of variation and selection does *not* diminish across such variations in historicity. Variation-and-selection and historicity are related but nevertheless different effects, and should not be confused. There is in fact a tendency to confuse them because the home domain of variation and selection is also a home domain of historicity: biological evolution. An important portion of the burden of this paper, in fact, is to try to pry loose the power of variation and selection forms of explanation from those of historicity (itself an emergent of variation and selection processes). If variation and selection is restricted to domains of significant historicity, its scope will be drastically reduced, and so also will the understanding of its ubiquitous importance.

*Macro-evolution toward cognition.* Macro-evolution at a biosphere level will tend to explore and occupy potential forms of system organization in several senses. System organization that is self main-

tenant in new conditions, new environmental niches, will tend to emerge and survive as long as those new conditions are available. Such a tendency would be a consequence of a pure random walk in the space of possible forms of adaptedness – of successful self maintenance – so long as the existence of particular instances enhances the probability of additional instances, e.g., through reproduction or catalysis. Such possible forms of adaptedness, in other words, form a landscape of partial stability of form of (adaptive) self maintenance. So, even if sulfur metabolizing bacteria didn't exist, there would be a probability that that potentiality would be realized eventually so long as the potentiality per se continued to hold.

System organizations that are *recursively* self maintenant across *new or broader* conditions will tend to emerge and displace organizations that require the same resources but are less adapted to them or to the variations in them. And systems that are highly adapted to variation per se – that are *adapted to adaptability* – will tend to emerge and become more adapted to such adaptability, more recursively self maintenant, over the macro-course of evolution. Adaptability is itself a form or a property of some potential adaptednesses (Bickhard, 1973, 1980; Hahlweg and Hooker, 1989). Highly developed adaptedness to adaptability will exhibit versatile forms of detection and adjustment, anticipation and adjustment, and even exploration and adjustment to variations and possible variations in environments – all involving various kinds of vicariants serving those functions of detection, anticipation, and exploration, such as distance detectors (Bickhard and Richie, 1983; Campbell, 1987). In the most developed forms, high adaptedness to adaptability will exhibit explorations of variations and *possible* variations in internal process organizations as well. In other words, highly developed adaptedness to adaptability will exhibit *cognition*.

#### *Adaptivity and Epistemic Fit: Representation*

High adaptivity requires the ability to adjust to alterations in the environment without death. Kinds of such environmental alterations that have been anticipated by evolution will generally yield various kinds of feedback organizations that detect, always vicariantly, relevant aspects and alterations in the environment, and that control appropriate internal or behavioral adjustments (Campbell, 1987).

*Anticipating lacunae of anticipation.* Not all possible alterations in the environment can be anticipated in the evolution of the species. Processes can be developed, however, by which some such adjustments to possibilities of the environment, such possible interactions with the environment, can be *learned* by the individuals of the species. This requires some principles of control of interaction which are themselves subject to variational alteration and vicariant selection with respect to how well they do in fact succeed in *anticipating* and *indicating* possibilities of interaction of the system and their consequences for the system (Barham, 1996; Bickhard, 1980, 1992c, 1993, 1998, 1999, 2002; Christensen and Hooker, 1998, in press; Krall, 1992).

*Indications of interactive potentialities are falsifiable.* Such indications of possible interactions are potentially false – they may not proceed or end in the manner indicated – and that falsity can in principle potentially be determined by the system itself, by trying out the interaction. Such functional indications of potential interaction, then, have crucial emergent properties of representation: they allow “falsification”, from the perspective of the system. Successful interaction is a form of *interactive knowing* of whatever is being interacted with. Elsewhere, in fact, it is argued that this form of emergent representation is the foundational form of all representation, and, thus, all cognition (Bickhard, 1993, 1998, 1999, 2000b, 2001, in press).<sup>5</sup>

Many issues must be addressed to fill out that claim, but the point of relevance here is that the fit of the *indicated* potential dynamics in a system to the *actual* potential dynamics afforded by the environment constitutes an epistemic fit (or lack thereof) between that system and that environment. This fit too is necessarily at root a product of variation and selection processes.

#### STATE SPACES

A powerful form of analysis and explanation is in terms of state spaces and constraints on dynamics within such spaces (Marmo, Saletan, Simoni and Vitale, 1985). We will focus in this section on the nature of state space analysis and explanation, some of the



limitations of this approach, and relationships with other kinds of explanation and analysis – especially variation and selection.

### *State Space Analysis*

A state space is a space of all possible conditions or states of a system. Necessarily, then, all possible dynamics of such a system will constitute movements in the state space. If the state space is defined well, with all relevant variables specified, those system dynamics will generally form mostly smooth trajectories within the space. Possible trajectories are determined jointly by various constraints on dynamics operating with respect to various possible initial conditions of the system.

A collection of particles, for example, will move in a state space formed by the three position coordinates and three momentum coordinates of each particle. If there are  $N$  particles, the state space will have  $6N$  dimensions. Basic mechanics will determine the overall trajectory of the system of particles in this state space for any given initial configuration of locations and momenta.

*Non-linear dynamics.* Physics engages in analysis and explanation within a state space formulation as one of its most basic tools. Non-equilibrium and non-linear systems analysis has introduced state space dynamic analyses much more broadly, such as into chemistry and biology. In the case of non-linear systems, the possible trajectories of evolution of the system can manifest bifurcations of a single trajectory into two or more possibilities – with the consequent necessity of the system somehow selecting which to follow – and can manifest the merging of different trajectories into a common path or point.

*Absorption.* There are a number of important qualitative distinctions that can be made concerning the organization of dynamics in a space of possible dynamics (Hirsch, 1984). One such distinction focuses on whether there exist regions of the possible dynamics of the system that are absorbing in the sense that, if the dynamics of the system ever enters such a region, it will never leave it.

*Attractors.* Another distinction, dependent on the existence of absorbing regions, is whether or not there is a tendency for the

system dynamics to enter absorbing regions. It is possible, even common, for some regions to be absorbing, but for entry of the dynamics of the system into those regions to be random and of low probability. On the other hand, some absorbing regions “attract” system dynamics in the sense that any dynamic trajectory within some broader region will move toward and into the absorbing region – as if the absorbing region attracted the system dynamics.

*Region shape.* Still another distinction is concerned with the shape of absorbing regions. They can exist as single points: absorbing states, or point attractors. They can exist as trajectories, either extended or cyclic. They can exist as regions, fractal or otherwise.

Some common forms of kinds of dynamic absorption, combining the above distinctions in various ways, are absorbing states, point attractors, trajectory attractors, and strange attractors:

- **Absorbing states.** Absorbing states, for example, are states with trajectories in, but no dynamic trajectories out (or at least low probability trajectories), as for crystal formation discussed earlier. If the dynamic space is organized such that any system whose state is within a certain subregion of the overall space will stay within that region, and that region contains one and only one absorbing state (and no other absorbing conditions), then the system is certain to ultimately end up in the absorbing state. This will be so even if the dynamics is random.
- **Point attractors.** A system may manifest possible dynamic trajectories that not only remain in such a region, but that *tend toward* the absorbing state from all points in the region. In such a case, the absorbing state is called a point *attractor*, and the region is the region of attraction.
- **Trajectory attractors.** A variant on this involves an attraction region in which the attractor is itself an extended trajectory. In this case, system dynamics will tend to move to the attractor trajectory, and then remain on it. An attractor trajectory might be cyclic, in which case a system will first move to the attractor, and then cycle around the trajectory indefinitely.
- **Strange attractors.** There are yet more exotic forms of such state space dynamics. For example, an attractor can not only be a point or a trajectory, it can exhibit fractal dimensionality.

In this case, it is called a strange attractor. Furthermore, it has been found that multiple regions of attraction can exist such that their attractors are not only individually strange, but that the differing attractors for the differing regions are fractally intertwined and intermixed with each other in what has been dubbed a fractal foam (*Science News*, 11/14/92; pg. 329; for fractally intermixed boundaries, see Nusse & Yorke, 1996).

*Explanation and attractors.* Note that if a system begins in some region of attraction and ends in the point attractor for that region, then the dynamic space view provides a form of explanation for that dynamics: That is simply what happens to systems with such dynamic spaces that find themselves in regions of attraction. That is the way such systems work.

*Trajectory splits and incomplete dynamic spaces.* Now consider bifurcated trajectories. If the trajectory splits into more than one possibility, then the selection of which one to follow is inherently random from the perspective of the dynamics under analysis. If that selection is determined by aspects of the system that are not in the given state space, then that split will not exist in a state space that *does* take those additional aspects into account. Quantum mechanics demonstrates that not all such split trajectories are simply the results of incomplete state spaces in this sense – state spaces that omit relevant variables. Furthermore, there is also good reason to believe that such splits in trajectories can be intrinsic, not just results of analytic incompleteness, at macro-system levels as well (Hale and Koçak, 1991; Nicolis and Prigogine, 1977, 1989; Nicolis, 1995; Prigogine, 1980; Wiggins, 1990).

*Dynamic spaces: Geometrization of explanation.* In all such cases, the dynamics of a system that can be described with a particular dynamic space can be predicted and explained in terms of the sorts of absorbing states; attractors; the shapes, locations, and sizes of the regions of attraction; and so on. That is, the possible dynamics of the system is precisely what the dynamic space approach is intended to capture, and, to the extent that it does that, it provides explanatory and analytic information for the dynamics of any particular instance of such a system. The topological and geometric properties of dynamic spaces model dynamic properties of the systems.

*State Spaces and Dispositional Analysis*

*Dynamic spaces as dispositions.* Explanations in terms of dynamic spaces are a species of dispositional explanation. Just as in the case of dispositional explanations of why billiard balls respond one way to being struck, while balls of putty respond differently, and of why gold responds with flattening and thinning to being struck, while chalk responds quite differently, so also can we explain system dynamics in terms of the dynamic dispositions captured in a dynamic space. The billiard ball and gold cases are, in effect, just a specification of simple dynamic spaces, defined by “being struck” or “not being struck” and by the differing consequences upon “being struck”.

Dispositional explanations are foundationally important to all of science. As mentioned, physics, for one, is built around state space dynamic analysis. Crucial physical concepts, such as mass or gravity, are dispositional concepts – they specify what would happen if certain conditions obtained. (Psychology, for one, has still not figured out that not all explanations are causal (Bickhard, Cooper and Mace, 1985; Bickhard, 1992; Cummins, 1983). Dynamic space analysis might do a major favor to psychology in that respect.)

*Explanations of dynamic spaces.* As dispositional forms of analysis and explanation, dynamic spaces are themselves subject to questions and further explanations. In particular, if a system evolves in such and such a way because its dynamics exhibit such attractors, we may question further why it is that the system exhibits a dynamic space with those properties. Dynamic space explanations are not “ultimate” explanations. Furthermore, the explanation of why a system manifests a particular dynamic space cannot be in terms of that dynamic space itself, on pain of circularity.

In general, there will of necessity be various constraints on the system process that intrinsically constrain it to that dynamic space and to the permitted trajectories in that space. These may be conservations, causal selections, or internal system dynamics, and so on, but they must be present in order for restrictions to particular spaces and trajectories within those spaces to hold. That is, the explanation of particular dynamic spaces will in general be in terms of lower level considerations of various constraints, of which the given

dynamic space is an emergent manifestation. In general, dynamic space analysis is analysis of manifest (dispositional) properties of underlying, perhaps internal, system processes, and those underlying processes may well be of variation and selection form. That is, *external* dynamical dispositions are in general explained in terms of *internal* dynamical dispositions.<sup>6</sup>

Given the ubiquitousness of quantum and thermal sources of disruption, in fact, it is necessary that both the continuing existence of a system manifesting some dynamic space and the constraints that hold that system to the trajectory constraints in that space be explicable in terms of some sort of selection satisfactions in order for the system organization to be persistent, and some sort of selecting constraints that explain the dispositional constraints described in the dynamic space (Bickhard, 1997b).

#### *Limitations of State Space Analysis*

*Unbounded dynamic spaces.* Dynamic spaces describe the dynamic potentialities of manifest system process. Not all system behaviors, however, are easily capturable in dynamic space terms. If the dynamic potentialities of the system are unbounded, for example, then the dynamic space must be infinite. Capturing this unboundedness is elementary mathematics if the space is constructable in terms of continuous variables, as is generally the case in physics. Describing an infinite space, however, may not be so “elementary”. If the space is discrete and the dynamics are nominal (no trajectories), for example, such as the discrete grammatical sentences of a language (the space of possible grammatical utterances), description of the space of possibilities can be more difficult.<sup>7</sup>

Finite description of infinite state spaces requires recourse to some recursive principle of generation of the space. In the case of continuous variable spaces, that recursive principle almost always has to do with the recursive definition of the real (or complex) numbers. In the case of sentences in a language, such a recursive description is called a grammar.

*Confusion between description and explanation: System processes and their spaces of dynamic possibilities.* Reifications of descriptions into purported explanations are quite common in the history

of science. Reifications of descriptions of dynamic spaces of some class of systems into “explanations” of why the relevant systems *manifest* those dynamic possibilities is just a recent example. The requirement of recursive generating principles for infinite dynamic space descriptions, however, can greatly increase the danger of such confusions: the recursivity of descriptions “sounds” like process, and can be confused with the actual explanatory processes in the system whose potentialities the space is trying to describe. Typical notions of competence-performance in psychology and linguistics constitute egregious examples – the grammars that describe the space of dynamic possibilities (grammatical utterances) are invoked as explanations of why and how people can and do in fact make grammatical utterances. The grammars, the dynamic spaces, are reified into the head of the speaker. In these cases, the recursivity involved in finitely describing unbounded classes of possible sentences is reified into purported processes or knowledge *in the person* that are supposed to *explain* those linguistic dynamic potentialities (Bickhard, 1980b; Bickhard and Campbell, 1992; Campbell and Bickhard, 1986, 1992). This is merely a circular category error.

*Necessarily incomplete dynamic spaces.* There is no apriori guarantee that the potential states, thus the potential dynamics, of a system *can* be exhaustively described – that the definition of the dynamic space can be complete. In the case of unbounded dynamic potentialities, recursive definitions of the space are required, but are not necessarily possible. In particular, the complete specification of the space requires complete specification of the relevant aspects and conditions of the space, and that specification can not always be accomplished.

The dynamic space of possible evolution of the biosphere is one example of a space that cannot be fully specified. As we discuss below, however, unspecifiability does not necessarily preclude investigation of some of the properties of such spaces.

Consider, for another example, a complex feedback *process*. If the feedback is strictly in terms of continuous variables, then the space of its dynamics might be definable. If the feedbacks involve nominal environmental conditions, however, then there might not be any recursive way to capture all of those conditions – and, there-

fore, there might not be any way to complete the dynamic space definition.

*Goal directedness.* A goal directed system can manifest an unboundedly complex potential dynamics with respect to the unbounded and not-recursively-definable space of environmental conditions within which the goal directed system might possibly be functioning. In such a case, the “goal directedness” of the system could not be captured in dynamic space terms because any such space would be necessarily incomplete relative to the full dynamic potentialities of the system.

Overlooking this point can yield, for example, an attempt to capture goal directedness in terms of the existence of attractors in a dynamic space, but such a criterion would count a rock rolling down a hill or water draining out of a bathtub as goal directed. It might seem that the problem is “merely” that the dynamic space has not been sufficiently specified in its full complexity, but the assumption that such dynamic space enhancement can suffice presupposes that all dynamic spaces are capable of complete specification, and that presupposition is false.

The problem is that even quite simple (and, therefore, finitely describable) organizations of system process can manifest potential dynamics that are not finitely describable. Unboundedness of the potential dynamics per se does not yield this undescribability, so long as the unbounded space is itself recursively describable (though other dangers lurk in this case). But the space of relevant environmental conditions with respect to which the potential dynamics of a system exist may well *not* be finitely describable, recursively or not,<sup>8</sup> in which case the specification of the organization of process in the system cannot be supplanted, even descriptively – and certainly not explanatorily – by specification of its space of potential dynamics.<sup>9</sup> If internal process models could always be supplanted by description of potential external dynamics, then behaviorism in psychology would have worked just fine.

Dynamical systems approaches are possible both for descriptive, or “phenomenological”, models and for explanatory process models. So, setting aside issues of the possible lack of recursive specification of a state space, the descriptive dynamics of a system might be useful in dispositionally explaining some *particular*

activity, or property of activity, of the system – the dynamic space contains an XYZ attractor, perhaps – but explaining *why* that system manifests that dynamic space requires more than a strictly external descriptive model. A model that includes the explanatory *internal* processes of a system that underlie its external dynamics can also be rendered in dynamic space form (often, anyway), but this is clearly a different kind of dynamic model. Dynamic spaces “merely” specify possible dynamic trajectories; they do not differentiate intrinsically between descriptive dynamics and explanatory dynamics – perhaps, for example, in which the constraints that generate the dynamic trajectories are energy conservation constraints. Assuming, for example, that goal-directedness can be defined in terms of attractors in a dynamic space (Barham, 1996; Delattre, 1986) conflates and confuses the distinction between description and explanation – a frequent error, but no less serious for its frequency (Campbell and Bickhard, 1986).

*Dynamic spaces and variations.* Dynamic spaces can not only themselves be (sometimes) explained in variation and selection terms, they can also participate in higher level variation and selection processes and explanations. For example, in a non-linear system with bifurcated possible trajectories, *selections* at bifurcation points of one of the permitted alternative trajectories – which selection may itself be a manifestation of variation and selection at lower levels of process – might themselves constitute *variations* of the overall system with respect to some higher level selection principles, in which some trajectories yield selection-out, and some trajectories are permitted. For example, bifurcation *selections* with respect to alternative possible *constructions* of interactive system organization might constitute *variations* of that interactive system organization with respect to *selections for adaptedness* to particular environmental conditions or forms of environmental variation. In other words, in this example, selections at constructive bifurcation points *internal* to the system constitute variations with respect to the fit *between* the system and its environment.

More broadly, it is not the case that all or most complex biological systems self-organize into living systems; rather it is those that do constitute living systems that persist – that survive selection. This is the basic form of the historicity in biological evolution.



This necessity for surviving selection in order to persist is present both at the broadest level of living versus non-living, and at detailed levels of variations in adaptedness and adaptiveness. It is relatively well recognized that self-organization and non-linear bifurcations are sources of variation – that must survive selection.

We have argued that variation and selection explanation does not require historicity, and that it can involve internal selection as well as external selection, and we have illustrated some of the scope of such a broader conception of variation and selection across diverse kinds of phenomena. We do not yet, however, have a complete overview of the explanatory resources of variation and selection perspectives.

#### INTRINSIC CONSTRAINTS, INTERNAL SELECTIONS, AND INTERNAL CONSTRAINTS

Processes of variation and selection are the locus of several differentiable kinds of explanation. In this section, we examine a few salient examples of these, and then discuss some of the distinctions that generate the various kinds, including some kinds not explicitly discussed.

##### *Intrinsic Constraints*

Intrinsic constraints are constraints that are intrinsic to the ontology of the phenomena under investigation. If a model of that ontology is relevantly correct, then the constraints will follow with logical or mathematical necessity from that model. Intrinsic constraints are ontologically necessary constraints on what is possible for such systems.

*Modal selection.* Paradigm variation and selection constraints, such as in evolution, function via a tendency to “select out” actual instances, e.g., organisms, that fail the selection criteria. Paradigmatically, these instances are themselves physically real, and the selecting out involves the prevention of the continuation of the failed forms, either through elimination of the instances per se or through prevention of reproduction. Intrinsic constraints “select out” in this same general sense, and in some domains this may involve a selecting out of physical instances, but more broadly,

intrinsic constraints involve selections against the *possibilities* of system existence and organization – intrinsic constraints can manifest *modal* selections. That is, intrinsic constraints in some cases select against the possibility of certain organizations coming into existence at all, prior to any selections that might function once those organizations already exist. Intrinsic constraints can involve modal selections, not just actual selections.

*Constraints on variations.* Viewing intrinsic constraints as modal selections ignores the causal processes normally involved in selection. A slight shift in perspective shows intrinsic constraints to be constraints on possible *variations*. In this view, selection per se remains a process with regard to actual instances, but it is recognized that not all conceivable instances are equally likely to be produced and exposed to possible selection. In fact, in many cases, there are strong constraints on what is a possible variation – constraints that are intrinsic to the ontology of the phenomena at issue. Such constraints may impose various statistical properties on variations, or they may rule out whole subspaces or may impose strong relational constraints, such as sequencing, on possible variations.

In either the modal view or the “constraints on variations” view, it is obvious that intrinsic constraints will be intimately related to variation and selection explanations more generally, as well as to other forms of explanation too. Intrinsic constraint explanations are a very powerful form of explanation, and are ubiquitously found, for example, in physics. Nevertheless, they are rare and not recognized as a general form of explanation in most sciences, including biology and psychology (Campbell and Bickhard, 1986; Bickhard, 1992).

*Intrinsic constraints and dynamic spaces.* Intrinsic constraints can sometimes be usefully construed in dynamic space terms. In this case, the explanation of why the system manifests those dynamic dispositions is that it is logically or mathematically impossible for any instance of the given ontology to do otherwise. But there can still be the question of why the system has such an ontology in the first place, or why something with that ontology exists at all, just as there can be questions concerning why a system manifests such and such a dynamic space. The answer, the explanation, of the coming

into existence of an instance of such an ontology may well be in terms of variation and selection processes at other levels of analysis.

*Intrinsic constraints and other explanatory forms.* Intrinsic constraint and variation and selection explanations can have interesting interrelationships. Some intrinsic constraints, for example, may be explained by other intrinsic constraints. For example, a symmetry group in physics might be explained as a subgroup of a larger, more constraining, symmetry group. Other intrinsic constraints might be explained in terms of prior selections. The selection of a particular alternative in a symmetry breaking process with respect to a more complex symmetry would be one example. In such a case, the more complex symmetry constrains to a space of possible low energy stable conditions, but does not select within that space. If the energy in fact reduces to such a level, then random variations, either thermal or quantum mechanical, will select one of the permitted alternatives, and thereby break the prior symmetry. This can occur, for example, in the cosmological cooling after the big bang, or with respect to the symmetry breaking with respect to physical orientation that occurs in crystal formation or in magnetization (Anderson, 1984; Careri, 1984).

*Intrinsic constraints across domains.* Foundational physics is permeated with intrinsic constraints.<sup>10</sup> A central form of explanation, for example, is based on Noether's theorem, which states (roughly) that any generator of a symmetry of the dynamical processes will yield a conserved quantity in the dynamics (Sudbery, 1986). Such conserved quantities correspond to properties of particles and fields. If the predicted particles or fields are in fact known or found, postulation of the generating symmetry is supported. If an explanation of those particles or fields is requested, in turn, one explanation will be in terms of the symmetries of the physical dynamics. In other words, *if* the dynamics honor such symmetries, then it follows of mathematical necessity, *intrinsically*, that such particles and fields must exist.<sup>11</sup>

This form of explanation is not as common in other areas, but examples do exist. In psychology, one example is provided by Piaget's notion of formal operations. Formal operations are supposed to be ontologically constituted as internal operations on other internal

operations – on concrete operations. If this ontology holds, then it is logically impossible for formal operations to come into existence prior to concrete operations. Meta-operations are impossible if there are no first level operations in existence to operate on. The sequencing of concrete operations followed by formal operations in child development, then, is an intrinsic constraint given the basic ontology of the model. It can certainly be questioned whether that ontology is correct – whether concrete and formal operations, as Piaget defined them, exist – but the point here is the form of explanation, not the issue of the correctness of the model. **IF** this ontological characterization is correct, then it is impossible for formal operations to occur before concrete operations (Campbell and Bickhard, 1986). This is similar in its general form to: **IF** the action (physical dynamics) has such and such an invariance, then these conserved quantities *must* exist. Intrinsic constraints provide powerful forms of explanation, and are underappreciated in most sciences.

### *Internal Selections*

A cousin of intrinsic constraints are internal selections. Internal selections are selections on the dynamics (behavioral, developmental, or evolutionary) of a system or a kind of system that arise from internal conditions and activities of the system (Campbell, 1974b, 1987, 1988b, 1990b). Entrenchment constraints on possible evolution, of which embryological constraints would constitute one class of examples, yield a form of internal selection – evolution cannot support variations that massively violate extant embryological processes (Gilbert and Raunio, 1997; Wimsatt, 1986; Schank and Wimsatt, 1987; Whyte, 1965). Similarly, evolution cannot support phenotypic variations that are inconsistent with the rest of already existing phenotypes, even if the phenotypic variation in question might be adaptive in some other phenotypic context.

What constitutes internal selection and what constitutes external selection is in part a matter of how the boundaries of the system are drawn, but in many cases, the natural system boundaries will encompass selection effects on the system and its dynamics *internally*.

Non-linear systems that involve bifurcations in their activity, for example, will select one of the possibilities at the bifurcation point on the basis of internal selections. Upon reaching the bifurcation

point, random internal conditions and activities of the system will impose mutual constraints upon each other and on the remainder of the system, out of which one of the bifurcation possibilities will emerge (Careri, 1984; Nicolis and Prigogine, 1977, 1989; Prigogine, 1980). Which exact pattern of Benard convection cells, for example, will emerge in a layer of water heated from below will depend on such conditions as the water depth, the geometry of the sides of the container, and the temperature differential between the bottom and top of the water, but, within the possibilities left open by such conditions, the pattern will emerge from the internal selection effects of the mutually constraining influences of the random motions of the water molecules. It is these random internal constraints that *internally select* which of the bifurcation possibilities emerges into actuality.

Internal selections share with intrinsic constraints the property of being capable of modal selections. They do not necessarily select-out actual systems that have already come into existence, as in evolutionary selecting-out of an organism, but, rather, can select within a set of possibilities which one(s) will come into existence (Campbell, 1974b). Such selections within possibilities can be either in the sense of selecting which possibility will be actualized, as in the convection cell example, or in the sense of selecting-out some of what would otherwise be possibilities, as in the case of entrenched embryological conditions selecting against inconsistent embryological paths.

Internal selections and intrinsic constraints are not the same, but they can overlap. First, not all internal selections are intrinsic constraints: the particular internal selections that yield an exact pattern of convection cells, for example, are not intrinsic to the ontology of that kind of system. Conversely, not all intrinsic constraints are manifested as internal selections: the sequencing of Piagetian formal operations after concrete operations is not dependent on internal selections, but *is* a consequence of intrinsic constraint. Internal selection and intrinsic constraint, however, can overlap: a phenotypic variant that could not mate with conspecifics, but that would be of greater fitness than conspecifics in other respects, would be eliminated by *selections* that would be *internal* to the evolutionary population, and that selection would instance a *constraint* that is *intrinsic* to all sexually reproducing such populations.

*Internal Constraints*

In many interesting cases, selections will manifest some more general constraint on what is stable or viable. Such a general constraint may not necessarily be logically intrinsic to the ontology of the system, and, therefore, will not necessarily constitute an intrinsic constraint, but can result from causal consequences of, for example, design and compatibility prerequisites. Entrenchment constraints, for example, will generally be realized by internal selections, but the entrenchment constraints on design that are so realized will be internal to the functioning of the system – they will be internal constraints. General design constraints on the workable morphologies and anatomies of plants and animals, or attractors in the spaces of such possibilities, may not be logically or mathematically intrinsic to the ontology of those organisms, but they can nevertheless be physically or chemically unavoidable, and, therefore, can impose strong internal constraints on what survives or reproduces or remains stable (for an extensive discussion with respect to plants, see Niklas, 1997, reviewed in Soltis, 1997; see also Moore and Brooks, 1997).

Internal constraints are much like intrinsic constraints, but they are not logically or mathematically inherent in ontology. Internal constraints, therefore, are more likely to be manifest in selections, perhaps internal selections, on variations that have been actually produced, in contrast to intrinsic constraints which tend to limit possible variations prior to any selections. For some explanatory purposes, these differences will not be of much importance and intrinsic and internal constraints will be equivalent. The two kinds of constraints, however, will in general manifest themselves differently with respect to the causal processes by which they are realized – impossibilities of variations in the case of intrinsic constraints, and selections on produced, or “in construction”, variations in the case of internal constraints – and for some purposes, those differences will be important.

*Explanatory Distinctions about Variation and Selection Processes*

Intrinsic constraints, internal constraints, and internal selections are three of a larger structure of interrelated explanatory kinds that involve variation and selection processes. These differing kinds

of explanation are generated by several distinctions that can be made regarding which parts and aspects of variation and selection processes are of focal importance.

A first distinction is between selections that are exerted from processes external to those being selected and selections that are internal. As discussed above, this distinction is at least in part derivative from what unit boundaries are involved in the analysis – external can become internal, and vice versa, with a new analytic boundary.

A second distinction is between the selection processes per se and more general sources of and explanations for systematicities of such selections. We have called these constraints.

Some constraints impose selections on particular instances of systems once they have been produced, while other constraints prevent conceivable variations from ever coming into existence at all. If the generation of system variations involves a protracted process of its own, such as embryogenesis, then constraints can also apply during such a process. Whether this is considered as a selection of variations or a prevention of variations is immaterial so long as the possibility and its own particular properties are recognized. For some purposes, this possibility would be usefully considered to be a third category in-between constraints on variations and selections of fully produced variations.

Still another set of distinctions has to do with kinds of constraints involved. Intrinsic constraints are those that derive from logical or mathematical considerations at the level of the ontology of the phenomena involved. There can also be metaphysical, morphological, causal, functional, physical, chemical – and so on – sources of constraint.

These distinctions cross each other to generate multiple possibilities of explanatory regularities. For our current purposes, it is less important to completely map this space, or to list all relevant generating distinctions, or even to draw exact boundaries, than it is to demonstrate that there *is* such a space, and that classical external causal selection of phenotypes occupies just one region in that space. Intrinsic constraints, internal constraints, and internal selections are among the most important of the commonly overlooked possibilities, but they are not the only ones.

## THE RATCHETED HIERARCHY OF STABLE EMERGENTS

In a metaphysics of *substances*, new substances cannot come into being. Only new mixtures or combinations of substances already in existence are possible. The notion of substance *emergence* in such a view is either inconsistent or supernatural.

In a universe furnished with organizations of *processes*, however, new organizations inherently have new properties. The new properties of a particular new organization may or may not be interesting or important, but the novelty of at least some of the properties is assured by the novelty of the organization. In this view, emergence is ubiquitous (Bickhard and Campbell, 2000).

If a new organization with its intrinsic new properties comes into being, however, for only a fleeting moment, its consequences for the rest of the universe are likely to be also fleeting and ultimately inconsequential. *Consequential* emergence requires, in most instances, persistence of the organizational form that manifests the emergence. With such persistence, consequences of emergents can ramify – including downward into lower levels of organization (Campbell, 1974b, 1990b). This persistence can be of two kinds, not mutually exclusive: (1) a *stability of particular instances* of the new organization, with accompanying stability and persistence of whatever its new properties may be, and (2) an *enhanced probability of the formation of new instances* of the organization, by, for example, self-reproduction or auto-catalysis.

Both sorts of persistence are possible only insofar as the relevant internal and environmental sources of disorder and dissolution are defeated. That is, both sorts of persistence require that the new organization satisfy selection pressures. At a minimal level – with regard to external selection – this may involve the energy-well of some organization exceeding in its depth the thermal energy in the environment that would otherwise break up the organization; at more complex levels, this might involve an agent being able to anticipate variations in environmental conditions and anticipatedly take action to block their effects – avoiding a predator, for example.

New organizations of process that are persistent, with accompanying emergent properties, yield new potentialities of still further organizations with their own emergents. The emergence of atoms in cosmological history, for example, makes possible the stable



forms of molecules. Stable sources of energy flow – stable entropy sinks – such as stars make possible the emergence of recursively self-maintaining open systems. Stable recursively self-maintaining systems make possible the emergence of systems that learn.

*Ratchets of possibilities of emergence.* That is, the emergence of new organizations of process that are persistent serves to ratchet the overall processes of cosmology and evolution, yielding new possibilities of (potentially stable) emergence in turn. It is clear, for example, that organisms that can *learn* to interact with their environments cannot precede organisms that can interact with their environments, and that organisms capable of cultural language cannot precede organisms capable of learning: there are intrinsic constraints on the ordering of emergence here. The emergence of successful interactive systems, then, ratchets the possible emergence of systems that can *learn* to interact, which, in turn, ratchets the possible emergence of cultural language.

According to a more detailed argument, in fact (Bickhard, 1980; Bickhard and Terveen, 1995; Campbell and Bickhard, 1986), interactive knowing makes possible learning, which, in turn, makes possible the evolutionary emergence of emotions, which, in turn, makes possible the evolutionary emergence of reflective consciousness – a progression of increasing adaptedness to adaptivity. The basic skeleton of the argument is:

- Knowing is a property of interactive system organization. (This requires extensive development, as well as extensive argument against alternatives, that will not be pursued here. See Bickhard, 1980b, 1993, 1999, 2000b, 2001, in press.)
- Learning, therefore, cannot be simply a matter of transferring impressions into the system from the environment – passive impressions from the environment cannot construct system organizations. Learning must be accomplished via internal variation and selection construction of system organization. The ability to engage in such constructions of organization is *additional* to basic innate interactive system organization – thus, learning must *follow* interactive knowing in evolution – and such a possibility of constructions will *increase* the adaptability of the systems.

- If a learning system received internal feedback of its own internal state of “well-definedness” of further interaction in the current environment, it could learn to interact with conditions of system-level functional “uncertainty about the environment” *generically*. That is, it could learn ways of handling uncertainty situations *per se* – it could run when in generic conditions of danger, for example, instead of trying out various behaviors randomly because it has never seen a tiger before. Such a system-internal feedback organization is clearly an addition to a basic learning organization – and therefore must follow learning – and it will increase the viability of the systems. It is a candidate model for emotions. The myriad issues of positive-negative emotions, specific emotions, the involvement of the self in emotions, sociality of emotions, emotional expression, and so on will not be addressed here (Bickhard, 2000).
- The organization of the possibilities for interaction in a system, insofar as they are correct, contain information about the environments that those organizations would successfully interact with. If a second level interactive system could interact with an first level interactive organization, it could learn to use that information – to “trace” it, in effect – in order to anticipate the environment and to plan actions in that environment. Emotions already involve feedback of process-uncertainty information; this would involve feedback of more elaborate organizational information to a second level interactive system. Such reflections on the system’s own internal processes and organizations is a candidate for reflective consciousness. This internal reflection architecture is an elaboration of the feedbacks already involved in emotions, and therefore must follow them. And the abilities, such as planning, to which it gives rise yield an increase in adaptability (Bickhard, 2001, in press).

The hierarchy, then, is arguably a hierarchy of macro-evolutionary ratchets in the sense that each step is a modification of or addition to the preceding, and each step increases adaptability. This entire hierarchy, in turn, constitutes an *envelope* of necessary ratchets for still further emergence: a species of systems that are capable of reflexive consciousness *and* emotions *and* learning *and* knowing

makes possible the emergence of language and culture (Bickhard, 1980; Campbell and Bickhard, 1986).<sup>12</sup>

The important point for current purposes is that ratchets of stability of emergent forms can form ladders and more complex hierarchies – hierarchies of some kinds of new organizations and emergents that make possible other kinds of organizations and emergents. Such hierarchies impose an organization on the potentialities of progressive emergence: these hierarchies constitute intrinsic constraints on the possible courses of cosmology and evolution. The crude hierarchy of interactive knowing to learning to language provides an example – independent of its *correctness*, its *form* illustrates a possible instance of such a ratcheting hierarchy. If correct, this hierarchy is a constraint, an intrinsic constraint in the state space of macro-evolution, and, therefore, on the dynamics of possible macro-evolution.

This point holds, if it holds at all, independent of any issues of evaluation of various locations or directions in such a hierarchy. If cosmology and evolution are in fact intrinsically organized in such manners, then that organization holds whether or not any particular emergent properties are picked out for positive or negative evaluation. Such hierarchies, in other words, are neutral with respect to issues of “progress” in evolution.

That evaluative neutrality, however, does not preclude the identification of various tendencies in evolution. The opportunistic exploitativeness of the evolution of the biosphere as a whole, for example, will tend to yield increasing exploitation of the various resources available as specializations emerge for the exploitation of untapped niches, or niches that are not as effectively exploited – so long as those resource selection constraints remain sufficiently stable. This is a sort of evolutionary niche version of the statistical mechanics tendency toward distribution in phase space. Of course, resource selection constraints may not remain stable, and the historicity of evolution, even disregarding external disruptions such as comets, provides a strong tendency for these to change over time as well.

Such potential opportunities, however, are not necessarily simply nominal niches that can be just moved into or taken over. Some such opportunities involve their own intrinsic constraints of hierarchies of

ratcheted emergences that, collectively as an entire hierarchy, can better and better exploit those opportunities. Progressively better exploitation of such niches, then, will involve progressive ratcheted emergences exploring the hierarchy of potential emergences. The evolution from one ratchet point to another may be of small probability in a non-foresighted evolution, but, nevertheless, the emergence of one stable form makes more likely than it was before the eventual emergence of a next location in the hierarchy of emergent possibilities. Once that new form does come into existence, it will tend to persist due to its own stability ratcheting, thus enhancing the probability of a next-in-the-hierarchy ratcheted location emerging. There will be a tendency, in other words, to climb such hierarchies over time, perhaps over major time frames.

In effect, these points are just elaborations of the simple points about absorbing states in a dynamic space or Markov process. In these cases, each (ratcheted) absorbing state (or set of states) is “relatively absorbing”, and each such state makes non-zero the probability of transition into some higher-in-the-hierarchy relatively absorbing state. A pure random walk in such a hierarchical organization of dynamic possibilities will manifest precisely the kinds of tendencies that we are outlining. Just as a random process will tend to fill the available niches of adaptedness, so also will it tend to ascend hierarchies of ratcheted adaptedness – they are constraints of the architecture of the space of possibilities. The perhaps literal “random walks” of the earliest people to cross the land bridge into Alaska (assuming the correctness of this general model) were nevertheless constrained to reach southern North America before they reached northern South America, and that before they reached Tierra del Fuego – those are constraints of the “architecture” of the space of the possibilities for “walking”.

Hadrons to atoms to molecules to objects forms precisely such a hierarchy of ratchets. So also does the claimed organization among interactive knowing, learning, emotions, and reflexive consciousness. In the latter case, the claim is that the niche of adaptedness to adaptability is, just like all other persistent niches, likely to be better and better exploited over time.<sup>13</sup> This niche, however, perhaps like others, cannot be simply occupied in arbitrary manner: there are complex intrinsic constraints on the emergences of higher levels of

adaptedness to this niche, and evolution must honor them – however randomly. So, in this case, the tendency toward better exploitations yields a hierarchical tendency of macro-evolution (again, independent of any evaluative judgments).

#### EVOLUTIONARY INTRINSIC CONSTRAINTS: RATCHETS AND STATISTICS

The hierarchy of ratcheted stable emergents, from knowing to language, is a form of intrinsic constraint on the possibilities of macroevolution – on the state space for evolution. This hierarchy describes part of the structure of the space of possible macroevolutionary dynamics – the structure of the space or ensemble of possible biological systems. In particular, it describes a stability hierarchy of “close” emergents, in which adjacent pairs of emergents are “close”, or at least “closer”, but non-adjacent pairs are far apart. The “metric” in this space is a metric of macroevolutionary construction, with steps of construction or modification as the unit. Emergence at any level of this hierarchy makes possible the later evolution of the next step in the hierarchy; conversely, it is not possible for any level of this hierarchy to emerge without all preceding levels being already present.

*Intrinsic statistics.* A related and important class of intrinsic constraints on such spaces of possible evolutionary construction is concerned with the *statistical* properties of those spaces (Kauffman, 1993). For example, if the fitness distributions in ensembles of possible systems are extremely irregular – rugged – with respect to the underlying metric of possible constructions, then new constructions cannot hill climb, because any “nearby” construction will yield a fitness that is essentially uncorrelated with all prior points of construction, including the current one. Any given system, then, will likely have no systems of improved adaptedness available within nearby constructive space. An evolutionary walk in such a space is statistically certain to become trapped in a low local peak of adaptedness (Kauffman, 1993).

This statistical ensemble perspective of analysis has wide applicability (Eigen, 1992; Kauffman, 1993; Lewin, 1992):

- It can be applied to ensembles of linear chain molecules, such as proteins or RNA;
- It can be applied to ensembles of possible regulatory relationships among genes;
- It can be applied to problems concerning the origin of life;
- and it can be applied to processes of morphological cell differentiation and cell identity.

A general point to be drawn from such analyses is that blind variation process, such as mutation, are unlikely to overcome the dominant statistical properties of an ensemble – if the “best” domain in an ensemble is a very small portion of the overall ensemble, or if the “best” domain is spread throughout the space in thin wisps, then virtually any variation will leave that domain, and the noise of random variation will overwhelm the tendency of selection to maintain a population in that domain.

*Meta-ensemble constraints.* One consequence of this point is that evolution will tend to select *whole ensembles* of systems, not just systems *within* ensembles. Evolution will tend to select ensembles within “ensembles of possible ensembles”, within meta-ensembles. In particular, evolution will tend to select forms of system ensemble – regulatory gene relationships, for example – that have better statistical properties. Ensembles with correlated fitnesses for nearby constructions, for example, are necessary for those constructions to have any probability of succeeding over generations. If gene regulation evolution explores a space with adverse statistical properties, the population involved will not be successful over generations of random variations in that space.

Conversely, too strong a pattern of correlations will limit or eliminate variations in fitness produced by variations in system. In the evolutionary domain, selection ceases to have much effect because system alterations simply move to nearby highly correlated fitness system designs, and the population randomly drifts around large relatively flat plateaus of fitness. In the regulatory domain, all elements become fixed or frozen, and useful dynamics of the regulatory system become limited or cease.

*Constraints on dynamics: Of construction, regulation, activity.* In general, if the dynamic space is too complex, dynamics – whether

of evolution or of regulation or whatever – becomes *chaotic* and useless. Chaotic dynamics offers no reliability. Conversely, if the space is too limited in its dynamic possibilities, then those dynamics become so limited as to become *frozen* and useless. Frozen dynamics offers no variation or flexibility. Thus, among those systems that continue to evolve in a coherently organized form, there is a general tendency to evolve “to the edge of chaos” – the edge of chaos is defined as the boundary (which is demonstrably rather sharp in interesting cases) between chaotic dynamics and frozen or “solid” dynamics (see Kaneko, 1994, for a related, but alternative, proposal).

It is of interest that the general conditions which constitute the “edge of chaos” are conditions of the partial modularization of the overall dynamics. In such conditions, flexible dynamics can be useful within “islands” or modules of the space or system, while relatively fixed or frozen dynamics partition one system from another (Kauffman, 1993; Lewin, 1992). Such partitions, of course, might be partially permeable to control influences. These formal statistical considerations, then, have re-discovered Simon’s conclusion concerning the necessity for partially decomposable modularization in any system that is subject to random variation in its history and construction (Simon, 1969).

*The constructive organization of the space of possibilities.* The statistical considerations apply relative to the underlying **constructive** structure of the ensemble being considered. In the case of proteins of fixed length, for example, variations are limited to substitutions of amino acids at sequential points along the protein. In the case of regulatory systems, variations can be of the topology of regulatory *connections* or of the logical or mathematical *form* of the regulatory influences being propagated within that topology (Kauffman, 1993). Kauffman has also explored “long jumps” in some cases, in which, for example, the possibility of substituting for *multiple* amino acids in a protein at one step is considered. Such long jumps, however, do not change the basic statistics of the ensemble.

In the case of regulatory organizations, evolution can select for certain statistical properties in the ensembles of possibilities by, for example, limiting the topologies to having few connections into any regulatory element, or by exploring only certain relatively simple

forms of regulatory logics or mathematics within the regulatory elements. The basic constructive space remains fixed, however, by such limitations, except in the sense in which, if only certain sorts of regulatory relationships exist, and alternatives would require *multiple* construction steps to create – and if those multiple steps end up creating forms of systems that are more vulnerable to evolutionary noise of variations – then those domains of the ensembles that could be reached only via such multiple construction steps can be considered to be isolated away from the ensembles that evolution is actually exploring. Evolution will restrict to, will select for, a sub-ensemble.

So, these points introduce another kind of intrinsic constraint into the overall ensemble. In the “ensemble of possible ensembles” some sub-ensembles are much more vulnerable to random variational noise than other parts – where “sub-ensemble” is definable with respect to reasonable principles of evolutionary construction. Evolution will tend to stay in sub-ensembles that are not so vulnerable to chaos, either in evolutionary dynamics or in system dynamics. The evolutionary and functional levels of analysis are linked in this perspective in that the sub-ensembles of evolutionary space that are vulnerable to noise are vulnerable precisely in the sense that noise in those sub-ensembles is much more likely to create systems with chaotic dynamics – thus, not viable systems.

*The origins of life.* In another interesting example of the “ensemble of ensembles” level of analysis, Kauffman (1993) has made a fundamental proposal concerning the origins of life. Consider some set of molecules, each with some very low probability of catalyzing the formation of other molecules. With just a few kinds of molecules, the probability that any catalysis will occur is small, and the probability that there will be any loop of sequential catalysis, such that the loop is collectively autocatalytic, is drastically smaller. But, as the number of kinds of molecules increases, the possible catalytic relationships increase in number even faster, and so also does the possibility of autocatalytic loops and nets. There is a phase transition in this meta-ensemble at a point of sufficient size of the set of types of molecules – a phase transition below which virtually all ensembles have small proportions of catalytic relationships and autocatalytic loops and nets, and above which almost all ensembles



of possible catalytic relationships contain autocatalytic complex nets. Kauffman proposes that this statistical inevitability in sufficiently complex ensembles within the space of meta-ensembles is a plausible form of origin of life. There can be many versions of such autocatalytic nets produced by the statistical “self organization” of catalytic relationships. From this variety of alternatives, external selection will select the most viable. This model requires further explanations of the evolution of simpler nets of catalysis and regulation since then, and of the evolution of DNA, and so on – issues which Kauffman addresses – but our current focus is on the sense in which this argument is another interesting illustration of the statistical meta-ensemble level of analysis.

Specifically, the meta-ensemble has an organization – an *intrinsic* organization – of the statistical properties of its constituent ensembles such that, with increasing size of the set of molecular species, there is a sudden shift in the probabilities of autocatalytic, self-sustaining and self-creating, nets of catalysis. This is a purely statistical emergent, and intrinsic constraint, in the meta-ensemble of possible catalytic molecular relationships.

*Self-maintenance.* Note that such autocatalytic nets are self-maintenant, in the sense discussed earlier, simply by virtue of being autocatalytic. They are also, in an interesting way, *recursively* self-maintenant: in this case, the form of exploration of alternative ways of being self-maintenant, in response to alterations in conditions, is a statistical exploration of “nearby” types of autocatalytic nets. If those nearby nets do not have correlated fitness – if the landscape is too rugged – then the statistical exploration that constitutes recursiveness of self maintenance will fail.

*New modes of construction yield new organizations of the space of possibilities.* Such properties and structurings of “ensembles of ensembles” may well be of critical importance in understanding, for example, the forms of organization of genetic regulatory systems or the origin of life. But again we point out that, in these analyses, the forms of *construction*, and, thus, the underlying topologies and metrics, of the basic (meta)ensembles remain unchanged across the constituent ensembles. This point is of importance because it is *not necessary* that they remain unchanged. In fact, Simon’s (1969) point

about hierarchies of functional modules illustrates an alternative possibility.

In particular, if successive constructions can make use of previous constructions as units or elements of construction – if construction is recursive in that sense (Bickhard, 1992b) – then the underlying constructive topology and metric of the space of possible systems or of possible dynamics can be radically changed by the creation of a new such unit of construction. With such a new unit of construction, a single constructive step of joining that unit with some previously existing unit will be just that single constructive step “distant” in the new constructive space, but might well be *many* steps distant in the old constructive space. Rearranging and recombining *segments* of proteins as building blocks in the construction of new proteins, for example, may be a highly adaptive change in the constructive space if those protein segments have some likelihood of functionality per se, so that such recursive constructions can use units of construction that are already (likely to be) functional. In effect, this is one form of the construction of (fallible) heuristics in constructive variations – use units of construction that have already worked.

Such heuristics constitute altering the constructive metrics involved, not just exploring the same metrics differently. Recursive, thus heuristic, construction is in that sense *not* equivalent to “long jumps” in the original space. A *particular* recursive construction will be equivalent to some *particular* long jump in the original space, but the set of possible such long jumps is much larger than the comparable set of possible such recursive constructions. That is, most long jumps will not be equivalent to heuristic recursive constructions, so a long jump strategy will in general be a much weaker strategy than a recursive, heuristic, change in the constructive metric being explored. The statistical properties of the two forms of construction will be entirely different.

Another form of recursive construction is to re-use already functional units not as single units in new constructions, but as the framework for further modification. Refinements, differentiations, specializations, and so on, of existing functional dynamic modules constitute additional forms of recursive, heuristic, construction. Such heuristics, of course, only work if the space of possible

systems is internally correlated in certain ways – such that variations on prior success is more likely to succeed than pure de novo randomness, but we already know that forms of such correlation are necessary for evolution to succeed anyway. Recursive heuristics are a way of further exploiting that statistical information in the ensembles of possibilities.

Such general recursive forms of construction, in turn, make contact with ratchets of stable emergents such as those among knowing, learning, emotions, reflexive consciousness, and language. Each step of this sequence, so the argument goes, constructively requires the preceding form of system, and each step yields an increase in adaptability. The overall sequence, then, is a path of possible macroevolution. It is a possible path, however, *only* for recursive constructions – constructions that make us of the products of previous constructions. Random singleton substitutions at the constructive level of DNA base pairs will never climb this sequence – will climb it with probability essentially zero.<sup>14</sup> Unless the constructions are themselves recursive, so that the emergence of one level of this sequence enables the closer exploration of modifications of that level – enables the constructive variational exploration of regions nearby that form of system – any ascent of the sequence becomes miraculous.

It is not only the statistics of the space that must permit heuristics, such as hill climbing, but it is also necessary that the constructive processes themselves – the sources of variation – permit those statistical properties to be utilized. In the case of hill-climbing, the heuristic is already intrinsic in the constructive process of single step constructions, so long as the statistics of the space makes hill climbing a reasonable heuristic at all. In such a case, the relationship between the topology and metric of the underlying space and the forms of construction can be obscured. In particular, it can be overlooked that the space is organized by the forms of construction, and that those forms of construction can themselves change. Recursive construction is an example of a relatively simple constructive *process* that nevertheless alters the constructive *metric*, and likely also the topology, of the space that it is constructively exploring with each new successful construction. The statistics of those spaces – whether the fitness landscapes on them are rugged

(uncorrelated) or smooth (correlated), for example – depends on the underlying metrics and topologies as much as it does on the fitness values per se. So changing the constructive processes changes the underlying metric, and, therefore, changes the statistics of the ensembles being explored – sometimes in adaptive ways.

In other words, for a recursively constructive process, new constructions change the constructive topology for further constructions. The variation and selection constructive processes, therefore, are not only exploring possibilities of particular organism (or system) organizations, but are also exploring possibilities of such constructive topologies. Just as some fitness landscapes will be too rough, too uncorrelated, to be viable over generations, so also will some fitness landscapes have bad topologies in other senses – perhaps successful constructions are too far apart to be reachable – for exploring those landscapes. In the “ensemble of possible ensembles”, it is not only the statistics that impose constraints, but also the possibilities for constructive heuristics.

Both the statistical and the heuristic “ensemble of ensembles” constraints are properties of the underlying constructive topologies. They differ in that bad statistical properties, for example, are those in which fitness disappears too quickly nearby to points of high fitness, while the heuristic properties are manifestations of how far apart successful constructive changes in fitness are relative to the constructive topology. If they are too far apart, they might as well not exist – they are not real dynamic possibilities for that constructive topology. They are not connected to simpler possibilities by a realistic constructive trajectory of relatively nearby points that are themselves viable relative to selections (Bickhard, 1992b). The explorations, therefore, will not only be of possible organism or system organizations, but also of possible constructive topologies for those organizations.

This move to a more general consideration of the variation and selection exploration of constructive topologies with good properties – e.g., statistical and heuristic properties – suggests still another level of possibility. If we focus not on organism or system level constructive changes, but on *trajectories* within spaces of *possible constructive topologies*, we encounter the possibility that some forms of (recursive) construction explore these meta-spaces

better than others (Weber and Depew, 1996). Furthermore, at still another level, some forms of construction are themselves better suited for modification of their own – variation and selection modification of the processes of construction themselves – into still more successful forms of construction (see the discussion of *meta-recursive* constructive processes in Bickhard, 1992b). That is, there may be better and worse ways to explore the space of possible constructive topologies, better and worse spaces to begin in for doing so, and better and worse processes of construction to begin with.

*Structural constraints in meta-ensembles.* These considerations yield another form of meta-ensemble analysis. There may be interesting changes in the statistical properties of a meta-ensemble – and even emergent phase shifts in those statistical properties, as in Kauffman’s analysis of a possible origin of life – but there may also be changes in the topologies and metrics of the ensembles, in the structural relationships among the ensembles, in a meta-ensemble (with consequent changes in the statistics of those ensembles), as are induced by recursive constructions. The hierarchy of knowing to language is an example of the latter form of meta-ensemble analysis – the importance of each step in this sequence constituting an evolutionary ratchet is precisely that it thereby alters the constructive space that evolution can explore thereafter. The emergence of recursive self-maintenance, for another example, is on one hand an absorbing point in a meta-ensemble of possible system organizations, and, on the other hand, an absorbing condition, a ratchet, that makes possible the evolutionary exploration of further ensembles and meta-ensembles.

*Evolution “despite” selection.* This dependence on the underlying forms of construction of the statistical properties – and other structural properties – of an ensemble of possibilities seems to be overlooked in, for example, Kauffman’s repeated claims for properties that have evolved “despite” selection (e.g., pp. 16, 24, 426, Kauffman, 1993). These “in spite of” properties are in general those that are explainable in terms of the statistical or other structural properties of the underlying ensemble – intrinsic and internal constraints and selections. Setting aside the teleological interpret-

ation of selection – selection as “trying” to do something, which is then thwarted by, say, the statistical properties of the ensemble – this view seems to be an objection to conceptions of variation and selection processes that presuppose flat unstructured probability distributions on nominalistic spaces of possible variations. An unstructured view of the space of possible constructions eliminates any contribution or constraint arising from the variation process itself. Such views, however, have never been realistic. Selections can only select among whatever variations are offered, and it will virtually never be the case that the space of possible variations is accessed in an unstructured space with a flat probability distribution. It should also be pointed out that such claims about “selection” writ large overlook the role of *internal* selection in the constructive and self-organizing processes being touted. So, as a *corrective* to such a simplistic view of variation and selection processes, and, therefore, an enrichment of such a simplistic perspective, Kauffman is quite correct: the organization of the space of possible constructive dynamics is an essential consideration. As a claimed *transcendence* of variation and selection processes, or a thwarting of them, however, Kauffman’s claims are misleading and in error.

*Evolution and equilibrium.* There is a further difficulty inherent in this general fitness landscape form of analysis. Such an analytic approach permits powerful studies of properties of equilibrium stability (and lack thereof) in such a space, and of possible trajectories (and lack thereof) of movement within such a space. But it does so with a focus on the properties of the space itself, and tends to obscure: (1) the possibilities of changes in the spaces involved, and (2) the influence of characteristics internal to the organism or species on such dynamics and stabilities. Recognizing that this framework presupposes the stability of the space itself highlights the possibility of unstable dynamic spaces, of unstable fitness landscapes. Adaptive spaces are dynamic not only exogenously, but also, for example, from interactions with other organisms and ecosystems, and as a consequence of interaction between the organisms and species whose adaptive spaces are at issue and their environments. Adaptation and adaptivity are not fixed externals. In fact, the attractors may change faster than they can be reached, so that there are *no* equilibrium stabilities, only continuing transients. The

dynamics *of* the spaces may be of equal importance to the dynamics *within* the spaces. The spaces involved may in fact exhibit dynamics with analyzable constraints and other interesting properties of their own, such as the generation of new and larger spaces that incorporate more information (Brooks and Wiley, 1988).<sup>15</sup> Analysis in terms of static spaces may distort understanding because of such presuppositions of the analytic framework being used.

Even if the state space is relative static, or at least is dynamic on long enough time scales for that level of dynamics to be ignored for particular purposes, it is still the case that important considerations are left out of this analytic framework. In particular, movement in such an adaptive space is not like a particle trajectory in which all relevant information is contained in the space itself and in the location of the particle (and perhaps other particles) in that space. Species trajectories may well be influenced by properties and constraints and dynamics *internal to* the species as well as by the space in which it moves. The only internal consideration that is analytically present in the standard framework is the topology of constructions, and even that, as we have seen, is obscured because there is only one per space – any dynamics of such topologies themselves are missing. But variations in a species are highly constrained by multiple internal properties and selections – intrinsic constraints, internal constraints, internal selections of many kinds. Such constraints on possible or viable variations encompass far more than constructive topologies, though those topological constraints are of immense importance themselves. Species retain a large “memory” of how they have arrived at their current points in such spaces, and those “memories” – such internalized information – have consequences that cannot be captured by a mathematical point in an adaptive space (Brooks and Wiley, 1988).

#### THE BIOSPHERE<sup>16</sup>

The evolution of the biosphere as a whole provides an interesting convergence of many of the themes discussed above. In particular, in spite of the fact that the dynamic space of that evolution cannot be specified, constraints on and within that space can be discovered

and investigated (e.g., Brooks and Wiley, 1988; Weber, Depew and Smith, 1988; Wicken, 1987).

Evolution is generally modeled in ways that accept organisms and species – especially sexually reproducing species – as given (Hull, 1988), and as paradigmatic. There are few left who would argue that species per se have essences, but there is nevertheless a common assumption that there is an essence to the *notion* of species, one that applies across the biosphere. Usually, that presumed essence is modeled after sexual species paradigms.

In fact, however, the boundaries between species can be highly problematic, with permanent and self-perpetuating hybrids; geographically separated but sexually compatible species; geographical distributions of species in which all local pairings are sexually compatible, but distant pairings may not be (Mayr, 1992); multiple grounds for species differentiation; and so on (Claridge, Dawah and Wilson, 1997; Ereshefsky, 1992, 1998; Frost and Hillis, 1990). Even the boundaries between *organisms* become unclear once exploration goes beyond the paradigmatic case. How many individuals are there in a clone of crabgrass that is spread over acres, some clumps connected by runners, and many no longer so connected?

What such examples suggest is that boundaries (and other forms of differentiation) in biological systems must themselves be explained, not simply presumed, and that there is no apriori reason to assume that all boundaries will be of the same kind, or that any one kind of boundary will be universally applicable. This question can be approached from a biosphere perspective in terms of the questions: Why are there any boundaries at all? What kinds of boundaries might be expected, and under what conditions? That is, why isn't the biosphere a panmixus with respect to all of its processes, and what and when would we expect instead?

The simple answer is that a biosphere panmixed process, of any kind, will have chaotic dynamics. No such biosphere could exist. A condition on the continued existence of the biosphere, then, is that it evolve modularizations that avoid panmixus. There is no need that these modularizations all be of the same kind, even if they are modularizations with respect to the same kind of process, and, clearly, the biosphere is constituted of intertwined multiple kinds of process. The overall pattern of modularizations, then, can be expected to be



complex – in kinds of modularizations, in conceptual relationships among those kinds, and in dynamic relationships among instances of those kinds.

*Cells.* Assume that something like Kauffman's autocatalytic web is a correct model of the origins of life (see Deamer, 1997, however, for strong alternative considerations). Such a web of chemical catalytic activity will be an open system, continuously recruiting raw materials and leaving end products that no longer participate in the processes. For such a web, there is no distinction between persistence of the web and the process per se – there is no "unit" or "instance" of the activity that is distinct from or superimposed on the activity. This has interesting consequences.

One is that there is no distinction between reproduction and growth of such a web. The simple persistence of the process is a reproduction of the pattern with new molecules, and is a growth of the process into new raw materials. If the spatial extent in which the various catalytic processes are occurring extends, should that count as growth – more of the same web – or reproduction – new instances of the web in new spatial volumes? In the similar case of a spreading fire, we tend to consider a larger descendent to be the "same" fire as its earlier version, unless something has meanwhile broken it into separated fires. This question does not necessarily have an answer: an indifferenciation between growth and reproduction might be the most accurate construal (Hull, 1988). The basic problem is that there is no clear distinction between the form of the process and separate instances of that form – there is no clear individuation of instances. Biological notions such as growth and reproduction presuppose that distinction, and it has not yet emerged in the case of a physically unbounded catalytic web.

The details of the chemical species involved in the web cannot in general be expected to remain fixed over time. Related chemicals will arise that will also participate in catalytic relationships, and may alter the organization of the web in various ways and to various degrees. The overall autocatalytic property of the web, however, will have to be maintained through such changes, or else this autocatalytic process stops. External selections will affect such evolution of the details of the web: those forms of the web that are most effective in various circumstances will tend to be the most common forms

in those circumstances (assuming a fitness landscape that is not too chaotic).

If we imagine the autocatalytic web spreading throughout all or most of the oceans, such variations in details of the chemicals involved and the consequent reactions involved in local areas will be very weakly coupled. An oceanic web, then, can be expected to be wildly complex in its overall dynamics – it will be chaotic. Such a vast autocatalytic web will not possess the reliability of self-organization in given circumstances that would be necessary to survive in those circumstances.

Cells provide a modularization of such a web. Cells move the chaos of too large a web back to the edge of partial decoupling between adjacent instances of the autocatalytic web. Cells individuate such instances. Autocatalytic webs that produce the materials for, and can function within, primitive cells will in that sense have a greater chance of finding web organizations that work and that will stay in the neighborhoods of such web patterns with sufficient reliability to maintain persistence of instances of the pattern.

By modularizing catalytic webs into distinct instances, cells yield a difference between growth and reproduction. They yield, therefore, the emergence of reproductive historicity – reproductive historicity has its own history (Hoffmeyer, 1997). *Natural selection* is a special form of variation and selection process, a form that involves such reproductive historicity. Cells, therefore, (perhaps together with DNA) yield the emergence of natural selection out of simpler kinds of variation and selection processes (Brooks and Wiley, 1988; Weber and Depew, 1996).

Cells satisfy a modularization constraint on catalytic webs; the *existence* of such a constraint, however, does not suffice to specify *how* that constraint is to be satisfied – how cells originated, in this instance. That remains a matter for additional theorizing (Barbieri, 1985; Eigen, 1992; Kauffman, 1993). Kauffman (1993) has addressed some manners in which, and reasons why, simpler catalytic organizations and DNA modulated catalytic processes might have evolved out of initial complex pre-DNA organizations. Barbieri's (1985) model involves a different path to DNA control.

*Infrastructure.* Cell boundaries are required in order to protect the organization of the dynamics internal to the cell. The *organization* of dynamics, however, and the dynamic processes themselves, are not identical. Cell boundaries help to protect the dynamics from external perturbations, but that may not suffice. In general, some sort of *infrastructure* is required to both make and to maintain the distinction between dynamics and its organization.

In a simple autocatalytic web, the reactants are also the infrastructure. They engage in *and* they organize the dynamics. There is no division of labor, no specialization of function (with respect to this distinction). More generally, however, there will be a separate infrastructure that guides and constrains and shields the dynamics. An infrastructure would have difficulty serving such a function if the dynamics of the infrastructure itself were changing at a faster rate than the dynamics that it constrains – in general, infrastructure will consist of longer time scale process organizations, perhaps even energy well structures, that are fixed relative to the usual time scales of the dynamics for which they are infrastructures.

All contemporary cells, including prokaryotes, contain elaborate infrastructural guides and constraints on their internal biochemistry. On longer time scales, DNA provides an infrastructural stabilization and buffering of reproductive dynamics, of the historicity of reproduction, and a stabilization and buffering of developmental dynamics and resultant trajectories (Weber and Depew, 1996).

In general, complex dynamics requires infrastructure. The evolution of such infrastructure and the constraints on such evolution is one of the less well explored areas of the field. Note that the internal constraint for infrastructure imposes powerful constraints on possible macroevolutionary trajectories. Infrastructure evolution is a prerequisite for much faster time dynamical evolution, and likely imposes its own ratcheting constraints (Buss, 1987; Smith and Szathmary, 1995).

*Organisms, growth, and reproduction.* Such units of patterns of living processes will tend to develop “interactors” – organisms – that permit extensions of adaptedness and adaptivity in wider and more varied circumstances (Hull, 1988). In the development of interactors, we find emergent intrinsic constraints such as Wimsatt’s embryological entrenchment, plus a host of internal constraints and

selections (Brooks and Wiley, 1988; Gilbert and Raunio, 1997; Oyama, 1992; Salthe, 1993; Weber and Depew, 1996). In general, for complex organisms, if it can't develop, it can't exist.

With cells, a distinction between growth and reproduction is introduced. With interactors, embryology and complex organisms. With complex organisms, evolution encounters in a new way problems of accumulation of error – dynamic “noise”. Not all kinds of error introduced during or after embryogenesis can be avoided or corrected. Some degree of error accumulation is inevitable, especially in infrastructure. Single instances of process organization, then – single organisms – become more prone to a certainty of error accumulation that, at least eventually, disrupts the process (Salthe, 1985, 1993). Reproduction is a solution to this ineluctable constraint. Reproduction is both a renewal of the embryological constructions that does not have to carry over error, and it is also a point of selection against error in the DNA modulators or in other parts of the core replicating processes. In other words, reproduction is itself a solution to constraints and selection pressures.

There is also a converse side to these selection considerations. Interactors can usefully be large – for locomotion, for example, or predation or capturing light. But larger size is not merely larger scale. In particular, larger size yields the possibility of wear and of the accumulation of error. Modularization and interaction, then, can select for increased size, but that encounters the cost of error accumulation – wear. Reproductive continuity, in contrast, does *not* necessarily need large size for the informational modulation of the generation of new interactors – for control of replication – but *will* be severely disrupted by error. Reproduction, therefore, cannot in general be engaged in and controlled at macro-levels with their inevitable accumulation of micro-level errors.

Quantum effects, however, often restrict the range of possibilities to discrete cases. Wear does not occur at quantum levels; wear is strictly a macro-level phenomenon. Error is still possible at quantum scales, but not the progressive accumulation of “micro”-errors. Discrete errors are also often able to be corrected.

Control of replication, then, would ideally be by something that was small enough to manifest quantum discreteness, but still large enough to carry adequate modulatory information. Inherent chem-

ical stability, of course, would also be nice. DNA molecules are quantum-small in two dimensions, but large in one dimension – that is, they are long and thin – thus capturing both quantum discreteness of errors and sufficient size to carry information for the modulation of replication.

As mentioned above, functionally differentiated “replicators” such as DNA do not replicate themselves per se. Rather they are functionally differentiated and functionally concentrated modulators of a larger process of reproduction. If separated from the processes that they modulate, DNA molecules do nothing. DNA constitutes a differentiation and partial modularization of the function of controlling reproduction and growth and development of a larger open system process. It is not DNA per se that replicates, it is the entirety of these larger processes (Oyama, 1992; Griffiths and Gray, 1994). It is the opposing selection pressures for size of “interactors” on the one hand and for quantum discreteness of possible errors on the other hand that yields this differentiation in size between organisms and reproductive modulators. More broadly, this differentiation needs explanation, rather than being simply presupposed.

*Sex.* In more complex systems, the introduction of correlated variations in correlated fitness landscapes can be a major asset, and sex is one powerful evolutionary invention that can serve that purpose. Sexual reproduction guarantees variation, and it guarantees variation that explores locations in the fitness landscape that are nearby to current locations – and, perhaps most important, it provides variations that are in units of genetic material that tend to be heuristically useful units. The fitness landscape for sexual sources of variation is not metricized by changes in single base pairs.

*Species.* An oceanic autocatalytic web would be chaotic, and consequently would not survive. For similar reasons, a world wide process of unconstrained sexual reproduction would be chaotic and would not survive (Mayr, 1970, 1996). Sex introduces heuristic sources of variation over generations, but it must do so with reliable correlations on the fitness landscape in order to enhance its heuristic success. The basic conclusion is the same as for the oceanic web: modularization, or at least partial modularization, is necessary.

Modularization is precisely what sexual *species* offer (Brooks and Wiley, 1988; Ereshefsky, 1992b; Templeton, 1992). Species are relative modularizations of reproductive activity in the biosphere. Without species, the biosphere would be reproductively chaotic, and chaos is strongly selected against. Species are primary participants in the historicities of evolution – they tend to perpetuate themselves, and they tend to perpetuate whatever selection pressures and niche opportunities that they participate in. The “reliability” of species, from a biosphere point of view, in constituting relatively persistent systems and consequent conditions, is on one hand a product of the modularization that they introduce, and, on another hand, the major source of historicity.

Asexual species have more limited sources of heuristic genetic variation, generally limited to variation within single genotypes (disregarding cross-species transfer such as by plasmids). The strong historicity of descent in such species tends to insure that cross-species reproductive chaos is not a threat, but the processes of variation *within* a reproducing individual must still be sufficiently reliable to avoid chaos. “What binds asexual organisms into species are the forces of selection, genetic homeostasis, and developmental canalization” (Ereshefsky, 1998, p. 112). This, of course, also holds for sexual species, but the cross-individual sources of variation for sexual species creates a pressure against the possibility that cross-individual variations are not also cross-species variations – that such variations are sufficiently close together in the overall fitness landscape.

Such a view of species differs markedly from the “class” or “set” view – from any essentialist view. This view of species is intrinsically dynamic, and cannot be captured in any static view (Sober, 1984, 1994). Species as dynamic modularizations have much more in common with the view of species as historically extended individuals (Ghiselin, 1997; Hull, 1984), including with regard to the potentially fuzzy boundaries between those individuals (Wiley, 1988). A potential lack of one-to-one correspondence between the modules induced by differing *sorts* of dynamics, however, might yield divergences even here (Ereshefsky, 1992, 1998; Mishler and Donoghue, 1994; Stanford, 1995).

Dynamic modularizations also capture the *anticipatory* nature of the species concept: incipient differentiation of a module may

proceed to a full differentiation of two or more distinct dynamic modules, or it may revert to an undifferentiated single module. Similarly, incipient differentiation of a species population may proceed to full speciation, or it may re-integrate. The designation of a differentiated population as a species involves anticipation of further differentiation into a distinct module (O'Hara, 1993).

*Ecosystems.* Cells modularize the catalytic processes of living systems. Species modularize reproductive processes. Material, energy, and information flows throughout the biosphere, in turn, are modularized by the dynamics of ecosystems (Brooks and Wiley, 1988; Salthe, 1985; Ulanowicz, 1986). The natural cycles of such flows (Barbieri, 1985; Schneider, 1988) cannot be unreliably chaotic. In each case, the modularization is a solution to the selective consequences of rigidity, on one hand, and unreliable chaos, on the other. Cells, species, and ecosystems are the Benard cells of their respective levels of process. Each level of modularization introduces its own dynamics, entrenchments, selective consequences, and other historicities into the broad evolution of the biosphere (Schneider, 1988; Weber and Depew, 1996; Wicken, 1988).

*Other constraints.* The dynamic space of possibilities for that evolution, in turn, is intrinsically constrained by the sorts of statistical considerations that Kauffman explores, and by the structural intrinsic constraints exemplified by the knowing, learning, language hierarchy. There are many constraints on that biosphere dynamic space, and they can be usefully explored even though the space itself cannot be fully specified.

*The biosphere as self-organizing system – at multiple “edges of chaos”.* Most generally, variation and selection have not, to date, functioned externally at the level of the biosphere as a whole. A single negative external selection at that level would be the end of life. Variation and selection, however, is a primary form of internal selection *within* the biosphere, and, as such, a primary engine of self-organization at the level of the biosphere. In fact, the processes of variation and selection are highly non-linear; the evolution of the biosphere manifests a nonlinear self-organizing dynamic, with internal variation and selection as its primary engine.

In this respect, the evolution of the biosphere is highly similar to other nonlinear self-organization: the competition among water molecules that produces some particular pattern of convection cells in a heated pan of water differs enormously in complexity from, but is nevertheless strikingly similar to, the competition among species that produces patterns of and alterations in the biosphere. Self-organization and variation and selection evolution are more intimately related than is usually considered (Depew and Weber, 1995).

Interestingly, then, even in variation-and-selection's home ground of evolution, when we consider the overall biosphere, we are forced to take into consideration internal selection – internal selection as involved in non-linear dynamics – and intrinsic constraints, of many sorts. The evolution of the biosphere is a non-linear, self-organizing, dynamic process – with variation and selection as the central sort of process at all levels, including that of the non-linear dynamics per se. The selections of evolutionary variation and selection are external relative to a species, but they are internal relative to the biosphere.

The biosphere too will tend toward the “edge of chaos” in its internal processes. A chaotic biosphere would not survive; a frozen biosphere would not survive. The modularizations that constitute the edge of chaos will take different forms for each of the different classes of processes in the biosphere: cells, species, and ecosystems with respect to enzymatic, reproductive, and matter and energy flow processes, respectively – though these process and their respective modularizations may not be as independent as generally assumed (Ereshefsky, 1992; Johnson, 1988; Mishler and Donoghue, 1994). Such tendencies do not require biosphere level processes, any more than Benard cells require pan-of-water level process. In all such cases, the organizational emergents result from local variation and internal selection.

Self organization of all kinds involves internal selection. Benard cells self-organize in a layer of water heated from below via internal variation and selection processes among the water molecules. There is no selection at the level of the pan of water per se – any such selection would eliminate the system. The biosphere self-organizes into cells, species, ecosystems, and so on, via variation and selec-



tion processes that are internal to the biosphere. There has been no selection at the level of the biosphere per se – any such selection would eliminate the biosphere (though a few external selection events may have come close to being at the full biosphere level). All self-organization involves variation and selection *internal* to the self-organizing system, which may well be *external* relative to modular components of that system, such as species or organisms.

The standard restriction of conceptions of selection to external selection, therefore, is artificial and misleading. What will be external selection relative to one unit of analysis will be internal selection relative to a higher level. To restrict variation and selection forms of explanation to external selection is to impose a theoretical constraint to something that is a property of the observer's frame of analysis, not a property of the phenomena per se.

#### SUMMARY

Recognizing the broad scope of variation and selection forms of explanation introduces their explanatory power far beyond the classical domain of biological evolution. Conversely, restricting variation and selection explanations to processes of external selection of organisms which have genotype regulated reproductive historicity is a failure to understand the scope of variation and selection explanations per se.

The historicities of biological evolution are additional explanatory considerations beyond those of variation and selection per se (though historicity per se is also not limited to biology), and such historicities themselves interact with and are partially explained by variation and selection processes: e.g., the modularizations, of many scales, and consequent historicities of those types of modules, necessitated by avoiding both the stasis of no variation and the chaos of unreliable variation. Variation and selection principles become a powerful addition to general explanatory resources, along with more classical such resources. The consequences of billiard balls striking each other will still require efficient causal explanations; why billiard balls function that way while putty balls do not will still require dispositional explanations; the lift provided by a wing will still involve boundary condition explanations; and why a system

manifested *this* trajectory rather than *that* one may still involve initial condition information. But phenomena from crystal formation to roadside gravel to multiple phenomena of evolution itself can be seen to fall with the scope of relevance of variation and selection principles. Some will be historicistic, and some not; and even for those that are historicistic, some will involve descent, and some not (at least insofar as descent involves the distinction between reproduction and growth).

Variations and selections, then, are characteristics of phenomena that are logically distinguishable from other characteristics such as historicity, especially historicity in all its complex richness in the biological realm of reproduction, phenotypes and genotypes, interactors and replicators, and so on. Variation and selection forms of explanation are valid and of broad scope when differentiated from such issues as historicity with which they are associated in biological evolution, the home domain of discovery of variation and selection forms of explanation. One of the primary aims of this paper is to argue that it is an invalid disservice to restrict variation and selection forms of explanation to realms in which particular forms of historicity can also be found. They are related, but distinct, principles, each powerful and important. But variation and selection does not *require* any form of historicity to be applicable.

Sources of selection are sometimes external to the system itself, as in biological evolution of a species with respect to an external environmental niche, but a important class of selection constraints are those that are intrinsic to, and may function internally to, the system itself and its dynamics – including that of the biosphere. Some variation and selection processes involve historicity, of various kinds, and some do not. Some derive from constraints – intrinsic, functional, and so on – that impose structure on the space of possibilities.

There are many variations on variation and selection. Variation and selection forms a powerful kind of explanation. It is ramified throughout the hierarchies of explanations of explanations that we find in science, including in physics and chemistry. In general, variation and selection is almost always the appropriate form of explanation when issues of fit or satisfaction are involved, especially concerning regularities of such fit or satisfaction.

## ACKNOWLEDGEMENTS

Deepest thanks are due to John Collier, Dave Cundall and, most especially, to Cliff Hooker for comments on earlier drafts, and to the Henry R. Luce Foundation for support to Mark Bickhard during the preparation of this paper.

## NOTES

1. The concept of emergence is itself problematic. For a defense of the metaphysical possibility of genuine emergence (see Bickhard, 1998; Bickhard and Campbell, 2000).
2. Of course, all instances of fit – of selection satisfaction – are *initially* fortuitous. This holds at whatever level of analysis may be involved. In biological evolution, for example, genetic mutations are clearly fortuitous relative to whatever usefulness they may prove to offer, but so also are broader phenotypic properties that may later prove to be useful, as addressed in the notion of “exaptation” (Gould and Vrba, 1982; Vrba and Eldridge, 1984).
3. We do not argue that evolution can be subsumed without remainder within a strict or simple variation and selection model – multiple additional phenomena must be accounted for. We do argue, however, that variation and selection as a general form of explanation does not require any of these additional phenomena, such as historicity, in order to be a potentially valid and relevant form of explanation (such as, for example, for crystal formation). In addition, we argue that many of those additional phenomena of biological evolution can themselves be explained within the general variation and selection framework.
4. Some interesting hierarchies of explanation emerge from this crystal formation example if it is asked “Why is the energy release successful?” That is, why doesn’t the kinetic energy that is released by the absorption of the atom or molecule into the crystal surface simply “turn around” and release the atom or molecule from that surface, with no net change? The answer, to a first approximation, is that that is exactly what happens – some of the time, but not, generally, all of the time. The energy will distribute over available forms of and locations for that energy in accordance with principles of statistical mechanics, and, if the phase space for the energy being distributed in some way *not* associated with the atom or molecule is large relative to the space that *is* so associated, the energy will tend to be “lost” into random transformations within that larger space. In general, that is, the overall system will move toward thermodynamic equilibrium. So, the first answer to the question of why the energy is in fact released, rather than simply reabsorbed with consequent release of the atom or molecule, is that the overall system will

tend to move toward equilibrium conditions, and that *may* involve “capturing” the energy elsewhere than in the crystal components.

A second question emerges at this point: “What explains the non-equilibrium condition of the system?” This involves the origin of the system and its relationships with the rest of the universe – specifically its being in a condition of lower entropy. In its *broadest* sense, the question becomes one of why the universe itself isn’t in equilibrium (note: another explanation in need of still further explanation), since the crystal formation process can proceed so long as it is in fact of lower entropy and “has some ultimate contact with the rest of the universe” (Feynman, Leighton and Sands, 1963, pp. 46–48). Even if the local system is (temporarily) thermodynamically isolated, the crystal formation can proceed so long as the *isolated* system is not in equilibrium – so long as it has been prepared, for example, such that the energy released by absorption into the crystal surface will not raise the temperature of the surrounding medium (e.g., gas or solution or melt) to the point that atoms or molecules begin to be knocked off of the crystal at a faster rate than they are absorbed. Creating such a system in initial disequilibrium itself requires “contact” with a universe not in equilibrium.

Related questions address the structure internal to a crystal (or other organized matter) already formed. Condensed matter physics addresses the properties and organizations that emerge from selections and constraints *internal* to a system (Careri, 1984; Anderson, 1984). These principles have also found fundamental applications in quantum field theory. Our focus in the discussion immediately above, however, is on the role of chance variation and energy-well selection in the initial absorption of particles in the formation of such systems: that is, in the role of variation and selection in the *process* of condensation, rather than the *resultants and emergents* of such condensation.

5. Representation is modeled in terms of interactive anticipation. Such anticipations yield emergent truth value – they can be (found to be) false, for the system itself. The function of such anticipation, in turn, is to serve the recursive self-maintenance of far from equilibrium systems. The function is to help maintain far from equilibrium conditions. Thus, representation is modeled as a kind of function, and function is modeled in terms of self-maintaining systems (Bickhard, 1993).

This general framework of explication is similar to that of Millikan (1984, 1993): representation explicated in terms of function, and function explicated biologically. But the relationship between representation and function here is quite different: Millikan’s representations are so because that is their evolutionary based function – it is what those representation’s predecessors were selected for. And the models of “function” itself are quite different. Millikan models function in terms of evolutionary history – what the evolutionary predecessors were selected for in the past. The interactive model outlined above is not fundamentally looking toward the past. It is an approach in terms of the maintenance of far from equilibrium conditions.

This is not the place for a detailed comparison, but it seems that Millikan’s model commits to an epiphenomenality that anyone committed to naturalism

should find unwelcome. Anything that is not derived from some appropriate evolutionary history cannot have a function in Millikan's view. So, if there are two lions present, one shipped directly from Africa and the other a molecular twin that just now happened to pop into existence by some cosmic accident, the heart of the Africa lion will have a function since it has the right evolutionary background, while the heart of the accidental lion will not have any function since it has no evolutionary history (Millikan, 1984, 1993). Yet the two lions, by assumption, will be identical in terms of current process and future potentialities of process. Therefore, whether or not anything has or serves any functions makes no causal difference to anything. In this view, function cannot be defined in terms of current physical state, but only current state is causally relevant. Function, therefore, is epiphenomenal. Derivatively, representation makes no causal difference; representation is epiphenomenal (Bickhard, 1993, 2000b, 2001, in press; Christensen and Bickhard, 2002). This should be a sufficient refutation of all etiological approaches to function (Godfrey-Smith, 1994) – they are inconsistent with a naturalism of function and of any model of representation based on them.

6. The exceptions are those cases, such as in the home ground of classical mechanics, in which there are no relevant internal processes, but are instead various constraints, such as conservation of momentum, that specify a manifest dynamics given initial conditions. At higher levels of analysis, any such constraints as may be found will in general be themselves explicable in terms of internal system processes, such as valence constraints on atomic combinations being explicable in quantum mechanical terms.
7. State spaces are usually understood as framing the manifest dynamics of a system – as constituting the space of possibilities within which such dynamics takes place, thereby tracing a trajectory in that space. It is odd to consider a space with no dynamics as a state space, such as a “space” of possible grammatical sentences. The use of the term “state space” is not what is at issue here, however. With or without dynamics, such spaces are intended to capture the possibilities of the system under consideration. They are descriptions of such possibilities, and the shared properties of such descriptions is what is of concern in this discussion. Even if we choose to restrict the term “state space” to a space containing dynamic trajectories, the points above about the underlying definitions of the descriptive spaces involved will remain. Conversely, text and discourse will trace trajectories in spaces of sentences, though they are likely to be not fully grammatical, and it is difficult (understatement!) to define a metric with respect to which such trajectories would be continuous, even if the description of the space per se were at hand.
8. At least not without intrinsic reference to the internal system organization itself.
9. Furthermore, it is not clear what would be gained even if the dynamic space description *could* be expanded to include all relevant variables: the expanded dynamic description must capture the internal dynamics of the goal-directed system, such as feedback processes. Otherwise, it fails to

capture the full relevant dynamics. In turn, that expanded dynamic space description either perspicaciously captures the goal-directed processes, such as feedback processes, or it does not do so perspicaciously. If it does present the goal-directed dynamics perspicaciously, then it at best becomes a different vocabulary for addressing the same phenomena as goal-directedness. If it does not, then it becomes a kind of obscuring of the relevant dynamic properties of the overall system.

10. Intrinsic constraints can apply for phenomena for which variation and selection may not be applicable. That is, intrinsic constraint as a form of explanation is not necessarily restricted to variation and selection processes. If intrinsic constraints prevent all but one possibility from coming into existence at all, so that there are no variations produced, then it is potentially not useful to explore a variation and selection perspective. As with most explanatory forms, however, there is no *a priori* guarantee that an analysis that precludes, or includes, variation and selection along with intrinsic constraints is correct. Even in the home ground of intrinsic constraints – fundamental physics – variation and selection explanations arguably have a role to play (Bickhard, 2003).
11. For further discussion of variation and selection forms of explanation in quantum field theory, see Bickhard (2003).
12. Don was concerned that motivation emerges with interaction – with knowing (Bickhard, 1997; Bickhard and Terveen, 1995) – and that the *later* emergence of emotion in this macro-evolutionary hierarchy might be confusing to readers. This assumes an equating of motivation and emotion, which certainly is common, but also false. The advantages of outlining the clear ratcheting hierarchy of knowing, learning, emotions, reflexive consciousness seems worth the necessity to point out that motivation and emotion are intimately related, but are not the same, and that emotion is a much later evolutionary emergence.
13. Godfrey-Smith (1996) appeared too late for Don and I to discuss it, but comparisons between the “adaptedness to adaptability” model, with its intrinsic structuring of evolutionary ratchets, and Godfrey-Smith’s complexity model are thought provoking.
14. New regulations can accomplish recursive constructions relative to the regulatory dynamics of what is being regulated, and such new regulations might be very “small” steps in a basic DNA substitution space, but this means of translating from recursive space to DNA space requires, in its general form, an extendable DNA space – a possibility of longer DNA molecules.
15. The notion of information here requires its own explication. See Brooks and Wiley (1988), Küppers (1990), and, most especially, Collier (1986).
16. This was the last section added to the paper. It was even more unfinished at the time of Don’s death than most of the other sections, and merits a much more developed discussion. Nevertheless, I have left it mostly as Don had seen it, save for considerable polishing and the addition of references. It provides, hopefully, a useful sketch.

## REFERENCES

- Anderson, P.W.: 1984, *Basic Notions of Condensed Matter Physics*. Benjamin/Cummings.
- Anderson, P.W. and D.L. Stein: 1984, Broken Symmetry, Emergent Properties, Dissipative Structures, Life and Its Origin: Are They Related? In P.W. Anderson (ed.), *Basic Notions of Condensed Matter Physics*. Benjamin/Cummings, 262–285.
- Barbieri, M.: 1985, *The Semantic Theory of Evolution*. New York: Harwood Academic Publishers.
- Barham, J.: 1996, A Dynamical Model of the Meaning of Information, *BioSystems* 38: 235–241.
- Bickhard, M.H.: 1973, A Model of Developmental and Psychological Processes. Ph.D. Dissertation, University of Chicago. Revised and edited version published as Bickhard (1980).
- Bickhard, M.H.: 1980, A Model of Developmental and Psychological Processes, *Genetic Psychology Monographs* 102: 61–116.
- Bickhard, M.H.: 1980b, *Cognition, Convention, and Communication*. New York: Praeger.
- Bickhard, M.H.: 1992, Myths of Science: Misconceptions of Science in Contemporary Psychology, *Theory and Psychology* 2(3): 321–337.
- Bickhard, M.H.: 1992b, Scaffolding and Self Scaffolding: Central Aspects of Development. In L.T. Winegar and J. Valsiner (eds.), *Children's Development within Social Contexts: Metatheoretical, Theoretical and Methodological Issues*. Hillsdale, NJ: Erlbaum, 33–52.
- Bickhard, M.H.: 1992c, How Does the Environment Affect the Person? In L.T. Winegar and J. Valsiner (eds.), *Children's Development within Social Context: Metatheory and Theory*. Erlbaum, 63–92.
- Bickhard, M.H.: 1993, Representational Content in Humans and Machines, *Journal of Experimental and Theoretical Artificial Intelligence* 5: 285–333.
- Bickhard, M.H.: 1997, Is Cognition an Autonomous Subsystem? In S. O'Nuallain, P. McKeivitt and E. MacAogain (eds.), *Two Sciences of Mind*. John Benjamins, 115–131.
- Bickhard, M.H.: 1998, A Process Model of the Emergence of Representation. In G.L. Farre and T. Oksala (eds.), *Emergence, Complexity, Hierarchy, Organization*, Selected and Edited Papers from the *ECHO III Conference*. *Acta Polytechnica Scandinavica*, Mathematics, Computing and Management in Engineering Series No. 91, Espoo, Finland, August 3–7, 1998, 263–270.
- Bickhard, M.H.: 1999, Interaction and Representation, *Theory & Psychology* 9(4): 435–458.
- Bickhard, M.H.: 2000, Motivation and Emotion: An Interactive Process Model. In R.D. Ellis and N. Newton (eds.), *The Caldron of Consciousness*. J. Benjamins, 161–178.
- Bickhard, M.H.: 2000b, Autonomy, Function, and Representation, *Communication and Cognition – Artificial Intelligence* 17: 111–131.

- Bickhard, M.H.: 2001, Function, Anticipation, Representation. In D. Dubois (ed.), *Fourth International Conference on Computing Anticipatory Systems*. American Institute of Physics, 459–469.
- Bickhard, M.H.: 2002, Critical Principles: On the Negative Side of Rationality, *New Ideas in Psychology* 20: 1–34.
- Bickhard, M.H.: in press, The Dynamic Emergence of Representation. In H. Clapin, P. Staines and P. Slezak (eds.), *Representation in Mind: New Approaches to Mental Representation*. Praeger.
- Bickhard, M.H.: 2003, Variations in Variation and Selection: The Ubiquity of the Variation-and-Selective-Retention Ratchet in Emergent Organizational Complexity Part II: Quantum Field Theory, *Foundations of Science* 8: 69–79.
- Bickhard, M.H. and D.T. Campbell: 2000, Emergence. In P.B. Andersen, C. Emmeche, N.O. Finnemann and P.V. Christiansen (eds.), *Downward Causation*. Aarhus, Denmark: University of Aarhus Press, 322–348.
- Bickhard, M.H. and R.L. Campbell: 1992, Some Foundational Questions Concerning Language Studies: With a Focus on Categorical Grammars and Model Theoretic Possible Worlds Semantics, *Journal of Pragmatics* 17(5/6), 401–433.
- Bickhard, M.H., R.G. Cooper and P.E. Mace: 1985, Vestiges of Logical Positivism: Critiques of Stage Explanations, *Human Development* 28: 240–258.
- Bickhard, M.H. and D.M. Richie: 1983, *On the Nature of Representation: A Case Study of James J. Gibson's Theory of Perception*. New York: Praeger.
- Bickhard, M.H. and L. Terveen: 1995, *Foundational Issues in Artificial Intelligence and Cognitive Science – Impasse and Solution*. Amsterdam: Elsevier Scientific.
- Brooks, D.R. and E.O. Wiley: 1988, *Evolution as Entropy*, 2nd ed. Chicago.
- Burnet, F.M.: 1959, *The Clonal Selection Theory of Acquired Immunity*. Cambridge.
- Buss, L.W.: 1987, *The Evolution of Individuality*. Princeton University Press.
- Campbell, D.T.: 1959, Methodological Suggestions from a Comparative Psychology of Knowledge Processes, *Inquiry* 2: 152–182.
- Campbell, D.T.: 1974a, Evolutionary Epistemology. In P.A. Schilpp (ed.), *The Philosophy of Karl Popper*. LaSalle, IL: Open Court, 413–463.
- Campbell, D.T.: 1974b, 'Downward Causation' in Hierarchically Organized Biological Systems. In F.J. Ayala and T. Dobzhansky (eds.), *Studies in the Philosophy of Biology*. Berkeley, CA: University of California Press, 179–186.
- Campbell, D.T.: 1987, Neurological Embodiments of Belief and the Gaps in the Fit of Phenomena to Noumena. In A. Shimony and D. Nails (eds.), *Naturalistic Epistemology*. Dordrecht: Reidel, 165–192.
- Campbell, D.T.: 1988a, Popper and Selection Theory, *Social Epistemology* 2: 371–377.
- Campbell, D.T.: 1988b, A General 'Selection Theory', as Implemented in Biological Evolution and in Social Belief-Transmission-with-Modification in Science, *Biology and Philosophy* 3: 171–177.



- Campbell, D.T.: 1990a, Epistemological Roles for Selection Theory. In N. Rescher (ed.), *Evolution, Cognition, and Realism*. Lanham, MD: University Press, 1–19.
- Campbell, D.T.: 1990b, Levels of Organization, Downward Causation, and the Selection-Theory Approach to Evolutionary Epistemology. In G. Greenberg and E. Tobach (eds.), *Theories of the Evolution of Knowing*. Hillsdale, NJ: Erlbaum, 1–17.
- Campbell, R.L. and M.H. Bickhard: 1986, *Knowing Levels and Developmental Stages*. Basel: Karger.
- Campbell, R.L. and M.H. Bickhard: 1992, Clearing the Ground: Foundational Questions Once Again, *Journal of Pragmatics* 17(5/6): 557–602.
- Careri, G.: 1984, *Order and Disorder in Matter*. Benjamin/Cummings.
- Christensen, W.D. and M.H. Bickhard: 2002, The Process Dynamics of Normative Function, *Monist* 85: 3–28.
- Christensen, W.D. and C.A. Hooker: 1998, Towards a New Science of the Mind: Wide Content and the Metaphysics of Organisational Properties in Non-linear Dynamical Models. Symposium on Mind, Special Issue, *Mind and Language* 13(1), 97–108.
- Christensen, W.D. and C.A. Hooker: in press, The Ascent of Endogenous Control: Autonomy-theoretic Foundations for Biological Organisation and Evolutionary Epistemology. In W. Callebaut and K. Stotz (eds.), *Bioepistemology and the Challenge of Development and Sociality*. Cambridge, MA: MIT Press.
- Collier, J.: 1986, Entropy in Evolution, *Biology and Philosophy* 1: 5–24.
- Cummins, R.: 1983, *The Nature of Psychological Explanation*. MIT.
- Cziko, G.: 1995, *Without Miracles*. Cambridge, MA: MIT Press.
- Davies, P.C.W.: 1984, Particles Do Not Exist. In S.M. Christensen (ed.), *Quantum Theory of Gravity*. Adam Hilger, 66–77.
- Claridge, M.F., H.A. Dawah and M.R. Wilson: 1997, *Species: The Units of Biodiversity*. London: Chapman & Hall.
- Deamer, D.W.: 1997, The First Living Systems: A Bioenergetic Perspective, *Microbiology and Molecular Biology Reviews* 61(2), 239–261.
- Delattre, P.: 1986, An Approach to the Notion of Finality According to the Concepts of Qualitative Dynamics. In S. Diner, D. Fargue and G. Lochak (eds.), *Dynamical Systems: A Renewal of Mechanism*. Singapore: World Scientific, 149–154.
- Depew, J.D. and B.H. Weber: 1995, *Darwinism Evolving*. MIT.
- Eigen, M.: 1992, *Steps Towards Life*. Oxford.
- Ereshefsky, M.: 1992, Eliminative Pluralism, *Philosophy of Science* 59: 671–690.
- Ereshefsky, M.: 1992b, *The Units of Evolution*. MIT.
- Ereshefsky, M.: 1998, Species Pluralism and Anti-Realism, *Philosophy of Science* 65(1), 103–120.
- Feynman, R.P., R.B. Leighton and M. Sands: 1963, *The Feynman Lectures on Physics*. Addison-Wesley.
- Frost, D.R. and D.M. Hillis: 1990, Species in Concept and Practice: Herpetological Applications, *Herpetologica* 46(1): 87–104.
- Ghiselin, M.T.: 1997, *Metaphysics and the Origin of Species*. SUNY.

- Gilbert, S.G. and A.M. Raunio: 1997, *Embryology*. Sunderland, MA: Sinauer.
- Godfrey-Smith, P.: 1994, A Modern History Theory of Functions, *Nous* 28(3): 344–362.
- Godfrey-Smith, P.: 1996, *Complexity and the Function of Mind in Nature*. Cambridge.
- Gould, S.J. and E.S. Vrba: 1982, Exaptation – a Missing Term of the Science of Form, *Paleobiology* 8: 4–15.
- Griffiths, P.E. and R.D. Gray: 1994, Developmental Systems and Evolutionary Explanation, *Journal of Philosophy* XCI(6): 277–304.
- Hahlweg, K. and C.A. Hooker: 1989, Evolutionary Epistemology and Philosophy of Science. In K. Hahlweg and C.A. Hooker (eds.), *Issues in Evolutionary Epistemology*. SUNY, 21–150.
- Hale, J. and H. Koçak: 1991, *Dynamics and Bifurcations*. Springer-Verlag.
- Hirsch, M.: 1984, The Dynamical Systems Approach to Differential Equations, *Bull. of the Amer. Math. Society* (new series) 11: 1–64.
- Hoffmeyer, J.: 1997, *Signs of Meaning in the Universe*. Indiana University Press.
- Hull, D.L.: 1984, A Matter of Individuality. In E. Sober (ed.), *Conceptual Issues in Evolutionary Biology*. MIT Press, 623–645.
- Hull, D.L.: 1988, *Science as a Process*. University of Chicago Press.
- Jerne, N.K.: 1967, Antibodies and Learning: Selection versus Instruction. In G.C. Quarton, T. Melnechuk and F.O. Schmitt (eds.), *The Neurosciences: A Study Program*. New York: Rockefeller University Press, 200–205.
- Johnson, L.: 1988, The Thermodynamic Origin of Ecosystems: A Tale of Broken Symmetry. In B.H. Weber, D.J. Depew and J.D. Smith (eds.), *Entropy, Information, and Evolution*. MIT, 75–105.
- Kaneko, K.: 1994, Chaos as a Source of Complexity and Diversity in Evolution, *Artificial Life* 1(1), 163–177.
- Kauffman, S.A.: 1993, *The Origins of Order*. Oxford.
- Krall, P.: 1992, A Model for Procedural Representation as a Basis for Adaptive Self-modification, *Evolution and Cognition* 2: 211–231.
- Küppers, B.-O.: 1990, *Information and the Origin of Life*. MIT.
- Lewin, R.: 1992, *Complexity*. New York: Macmillan.
- Lienhard, G.E.: 1973, Enzymatic Catalysis and Transition-State Theory, *Science* 180: 149–154.
- Marmo, G., E.J. Saletan, A. Simoni and B. Vitale: 1985, *Dynamical Systems*. Wiley.
- Mayr, E.: 1970, *Populations, Species, and Evolution*. Harvard.
- Mayr, E.: 1992, Species Concepts and Their Application. In M. Ereshefsky (ed.), *The Units of Evolution*. MIT, 15–25.
- Mayr, E.: 1996, What is a Species, and What is Not? *Philosophy of Science* 63: 262–277.
- Millikan, R.G.: 1984, *Language, Thought, and Other Biological Categories*. Cambridge, MA: MIT Press.
- Millikan, R.G.: 1993, *White Queen Psychology and Other Essays for Alice*. Cambridge, MA: MIT Press.

- Mishler, B.D. and M.J. Donoghue: 1994, Species Concepts: A Case for Pluralism. In E. Sober (ed.), *Conceptual Issues in Evolutionary Biology*, 2nd ed. MIT, 217–232.
- Moore, B.R. and D.R. Brooks: 1997, Externalist and Internalist Perspectives on Patterns of Ecological Diversification. *International Society for the History, Philosophy, and Social Studies of Biology*, Seattle, July 19.
- Nicolis, G.: 1995, *Introduction to Nonlinear Science*. Cambridge.
- Nicolis, G. and I. Prigogine: 1977, *Self-Organization in Nonequilibrium Systems*. Wiley.
- Nicolis, G. and I. Prigogine: 1989, *Exploring Complexity*. Freeman.
- Niklas, K.J.: 1997, *The Evolutionary Biology of Plants*. Chicago.
- Nusse, H.E. and J.A. Yorke: 1996, Basins of Attraction, *Science* 271: 1376–1380.
- O'Hara, R.J.: 1993, Systematic Generalization, Historical Fate, and the Species Problem, *Systematic Biology* 42(3): 231–246.
- Oyama, S.: 1992, Ontogeny and Phylogeny; A Case of Metarecapitulation? In P. Griffiths (ed.), *Trees of Life*. Kluwer Academic, 211–239.
- Prigogine, I.: 1980, *From Being to Becoming*. San Francisco: Freeman.
- Radnitzky, G. and W.W. Bartley: 1987, *Evolutionary Epistemology, Theory of Rationality, and the Sociology of Knowledge*. La Salle: Open Court.
- Salthe, S.N.: 1985, *Evolving Hierarchical Systems*. Columbia.
- Salthe, S.N.: 1993, *Development and Evolution*. MIT.
- Schank, J.C. and W.C. Wimsatt: 1987, Generative Entrenchment and Evolution. In A. Fine and P. Machamer (eds.), *PSA 1986 vol. II*. East Lansing, MI: Philosophy of Science Association, 33–60.
- Schneider, E.D.: 1988, Thermodynamics, Ecological Succession, and Natural Selection: A Common Thread. In B.H. Weber, D.J. Depew and J.D. Smith (eds.), *Entropy, Information, and Evolution*. MIT, 107–138.
- Simon, H.A.: 1969, *The Sciences of the Artificial*. Cambridge: MIT Press.
- Smith, J.M. and E. Szathmari: 1995, *The Major Transitions in Evolution*. Freeman.
- Sober, E.: 1984, *Conceptual Issues in Evolutionary Biology*. MIT Press.
- Sober, E.: 1994, *Conceptual Issues in Evolutionary Biology*, 2nd ed. MIT Press.
- Soltis, D.E.: 1997, Avenues for Plants, *Science* 277: 326–327.
- Stanford, P.K.: 1995, For Pluralism and Against Realism about Species, *Philosophy of Science* 62: 70–91.
- Sudbery, A.: 1986, *Quantum Mechanics and the Particles of Nature*. Cambridge.
- Templeton, A.R.: 1992, The Meaning of Species and Speciation: A Genetic Perspective. In M. Ereshefsky (ed.), *The Units of Evolution*. MIT, 159–183.
- Ulanowicz, R.E.: 1986, *Growth and Development: Ecosystems Phenomenology*. Springer-Verlag.
- Vrba, E.S. and N. Eldredge: 1984, Individuals, Hierarchies, and Processes: Towards a More Complete Evolutionary Theory, *Paleobiology* 10: 146–171.
- Weber, B.H. and D.J. Depew: 1996, Natural Selection and Self-Organization, *Biology and Philosophy* 11: 33–65.
- Weber, B.H., D.J. Depew and J.D. Smith: 1988, *Entropy, Information, and Evolution*. MIT.

- Whyte, L.L.: 1965, *Internal Factors in Evolution*. New York: Braziller.
- Wicken, J.: 1987, *Evolution, Thermodynamics, and Information: Extending the Darwinian Program*. Oxford.
- Wicken, J.S.: 1988, Thermodynamics, Evolution, and Emergence: Ingredients for a New Synthesis. In B.H. Weber, D.J. Depew and J.D. Smith (eds.), *Entropy, Information, and Evolution*. MIT, 139–169.
- Wiggins, S.: 1990, *Introduction to Applied Nonlinear Dynamical Systems and Chaos*. Springer-Verlag.
- Wiley, E.O.: 1988, Entropy and Evolution. In B.H. Weber, D.J. Depew and J.D. Smith (eds.), *Entropy, Information, and Evolution*. MIT, 173–188.
- Wimsatt, W.C.: 1986, Developmental Constraints, Generative Entrenchment, and the Innate-Acquired Distinction. In W. Bechtel (ed.), *Science and Philosophy: Integrating Scientific Disciplines*. Dordrecht: Martinus Nijhoff.

*Cognitive Science*  
*17 Memorial Drive East*  
*Lehigh University*  
*Bethlehem, PA 18015-3068*  
*USA*

Mark H. Bickhard

*Sociology and Anthropology*  
*681 Taylor Street*  
*Lehigh University*  
*Bethlehem, PA 18015-3169*  
*USA*

Donald T. Campbell