Introduction: dynamics all the way up

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Put in the broadest terms, “growing explanations” refers to what may be a sea change in the character of much scientific explanation. Over the past forty years, the hierarchy of the natural sciences has been inverted, putting biology rather than physics at the top, and with this inversion emphasis has shifted from analysis to synthesis. In place of the drive to reduce phenomena from higher-order organization to lower-lying elements as the highest goal of explanation, we see a new focus on understanding how elementary objects get built up—or better, are “grown up”—into complex ones and even a reconsideration of the nature of things regarded as elementary, like particles and genes. The essays in this volume reflect on the history of this development.

Because the essays deal with quite diverse subjects, readers looking for a point of entry suitable to their own knowledge and taste may do well to begin with the following survey of all of the essays and their relation to the theme of growing explanations. Its further exploration can then proceed in whatever order best satisfies individual interests. A brief afterword will collect several common threads.

Some markers of the change we are pursuing are the newfound prestige of biology; new institutes being established at major research universities to study building-up problems in both biological and physical sciences; and claims in fields from condensed matter physics to ecology that the problems of synthesis are every bit as fundamental as those of elementary particle physics, which has for some time been able to reserve the term *fundamental* for itself. In this scenario, the project to map the human genome, once touted as the answer to understanding human biology, has become a mere starting point, a catalogue compiled by mechanical means from which the real problems and answers will arise. Perhaps even more telling of how prominent this shift in perspective has become is the recent call from educators and scientists, reported on the front page of the *New*

York Times and widely elsewhere, for a reordering of the high school science curriculum. Students have long proceeded from biology to chemistry and then to physics as the culmination of their science education, reflecting the view that explanation ought to proceed from description and classification at the macro level to fundamental law and causation at the micro level. Inversion of this standard order would instead arrange the high school science curriculum according to the building-up principle—physics, then chemistry, then biology—beginning with unorganized matter and universal principles and culminating with higher states of organization and differentiation. At first sight, therefore, it seems surprising that the leading advocate of "physics first" has been Leon Lederman, Nobel laureate and prime organizer of that ill-fated emblem of elementary particle physics, the Super-Conducting Supercollider, and the author of a book promoting its virtues, appropriately titled *The God Particle.*[1]

But inverting the teaching order says nothing in itself about what is most fundamental. Lederman, for example, continues to hold reduction as the goal of science. Nevertheless, other advocates of "physics first" believe it reflects the importance of building up to complexity. From both perspectives, elementary units remain the building blocks of higher order structures: protons and neutrons for nuclei, atoms for molecules, amino acids for proteins, and so on. In this sense elementary things and the rules that govern them remain fundamental. But for those concerned with complexity, the elementary units are not the gods that will explain more highly organized structures. Instead, they put strong constraints on what structures are possible at the higher level. They establish necessary conditions but typically not sufficient conditions for determining what the higher structures will be or how they will behave.[2] "Complexity" names this problem. It is usually taken to go beyond the merely complicated to the irreducibly complex. That is the sense in which *complexity* is used throughout this volume.

It has often been said that the only way to understand an organism is to grow it. In an expanded sense of "growing," the same can be said of complex systems generally. Since the behavior of a complex system cannot adequately be explained in terms of its constituents, little option remains but to put it in action and observe the results. A full spectrum of results obtained from often-repeated trials may then provide considerable understanding of how the system works, in terms of shapes and periodicities, critical points for phase transitions or fractures, the function of particular parts in their interactions with other parts, and the form of those interactions, especially their nonlinearity.

Such features have always been difficult to observe, analyze, or model in a controlled way. So it is not surprising that the fascination with complexity in the post–World War II era has been closely linked with new technologies: microwaves, X rays, and electron beams to produce visual images of physical and biological structures; powerful means for sequencing and amplifying DNA; and a variety of mathematical techniques. Most important of all, of course, has been the computer, without which it would be impractical either to handle the large amounts of information required to map most complex behavior or to circumvent physical and mathematical complexity with computational schemes.

This power of the computer gives it a special place for the theme of growing explanations. When it is too difficult or expensive to grow up real systems, it is often possible to simulate their growth. Many of the sciences of complexity depend essentially on high-speed computers to iterate algorithms, thereby to produce finely controlled simulations of processes developing in time. Such virtual systems have the great advantage of transparency, at least in principle. Knowing the model on which a program has been built, one can hope to understand how it works, in the sense of seeing how it produces the range of particular outcomes that it does, even when predicting them in detail is not possible. That is, one grows their explanation. In a variation on the age-old theme that we know what we can make, contemporary investigators sometimes prefer the simulation to the real thing. A striking example reached the general public recently from Clyde A. Hutchison, a microbiologist involved, along with a number of others including J. Craig Venter, the controversial motor of the Celera Corporation, in decoding the genomes of very small bacteria. Hutchison offered his views on understanding life: “The ultimate test of understanding a simple cell, more than being able to build one, would be to build a computer model of the cell, because that really requires understanding at a deeper level.”

Interestingly, although Hutchison emphasizes that the relation of genotype to phenotype is complicated, he himself believes that “life can be explained from a reductionist point of view” and he and his coworkers suggest that the question “What is Life?” should be rephrased in genomic terms: “What is the minimal set of essential cellular genes?”[3] Others disagree, believing that the nature of life lies in the higher orders of organization that would emerge in building up any organism, whether real or virtual. This belief in the fundamental nature of complexity for living systems often appears in public forums (as it did in this case)[4] as though it were an inherently religious matter. Most scientists, however, take a thoroughly naturalistic view, even when drawing on religious metaphors. A rich perspective on formulations of this kind can be obtained by considering the nature of life as represented in the purely computational form of “artificial life,” or Alife. This volume will culminate in three such reflections.

Part I. Mathematics, physics, and engineering

Before considering the biological sciences, where the theme of growing seems most obvious but where issues of complexity involve the imposing subject of life itself, we begin with a series of essays on the recent history of the mathematical sciences. Although written from diverse perspectives about diverse subject matter, they will draw out several recurrent themes. One of these is the quite prominent role of topology as the mathematical route to understanding morphology, or how shapes develop in space and time. Closely related is a focus on the dynamic nature of the things we observe as more or less stable. And in this regard, phenomena and materials of the everyday world, in all of their diversity and contingency, have gained newfound respect and attention. Finally, related in different ways with each of these themes is the role of hybrids of all kinds: hybrid objects, hybrid research, and hybrid disciplines. Since morphology, dynamical objects, mundane phenomena, and hybridity are often linked almost exclusively with the sciences of complexity, it will be instructive to start out by looking at how some of those topics have appeared in the field that most often stands as the antithesis of complexity: elementary particle physics.

Elementary particles?

If the traditional ideal of explanation in the sciences of the twentieth century has been reduction and unification—reduction to elementary entities and unification under general laws governing those entities—the paradigmatic reference for that ideal has been elementary particle physics. And yet, recent developments suggest that even this field is undergoing a rather dramatic transformation. This is particularly true with respect to the nature of the objects regarded as "elementary." Only a decade ago, the elementary units were point particles without extension or shape. Now, if string theory may be taken as the reigning ideal for the future, they are entirely different sorts of things. As Peter Galison describes the recent history of string theory in "Mirror Symmetry: Persons, Values, Objects," the most elementary objects have become strings in ten dimensions whose "compactified" shape and size are critical parameters for the kinds of particles that exist in the familiar world of three space dimensions and one of time.

Strings, if they exist at all, are topological objects, or better, adopting the language of biology, morphological, characterized by their form and its development. A good historical analogue for the conceptual shift from point particles to strings is the attempt in the second half of the nineteenth century, especially by British theorists of electromagnetic fields (William Thomson [Lord Kelvin], J. C. Maxwell, J. J. Thomson, and Joseph Larmor), to represent the point masses and electric charges of action-at-a-distance theories as manifestations of vortices in an underlying, continuous substratum. Arrangements of these vortices would constitute not only the luminiferous ether but also chemical atoms, with the table of the elements being built up from increasingly complicated structures of interlinked and knotted vortices. And although the vortices themselves would not be accessible to empirical observation, their vibrations and oscillations would be detectable in the characteristic spectra of electromagnetic waves associated with the different elements. In other words, the vortices were characterized by their morphological properties in space and time: their shapes and periodicities. Like strings, but easier to visualize, they were essentially dynamical processes, in sharp contrast to the static point particles of previous theory.

In addition to this dynamical character, and again like strings, if the full mathematical articulation of vortices had met the requirements of established physical theory, they would have unified physical nature, reducing all three kinds of matter then thought to exist—ether, electricity, and ponderable matter—to a common foundation, including the forces between them, perhaps extending even to gravity. But there the problem stuck. On the one hand, no adequate mathematics existed for the full articulation of vortex motion, and on the other, existing physical theory and experimentation were not adequate to specify its properties.

This is the sort of situation that Galison finds particularly intriguing for strings, although at a much more esoteric level of both mathematics and physics. At the moment, the status of strings is uncertain, though they are full of promise. Neither fully mathematical objects nor fully physical ones, they live in a state of possibility. Most interesting of all, the people who investigate them find themselves in a similarly indefinite state. Having approached string theory originally from either the mathematical or physical side, they are uncertain of whether they are doing mathematics or physics and they find it difficult to communicate with their opposite members. Thus they have set out quite consciously to develop modes of communication that will make it possible to exploit the capacities of both mathematics and physics. Galison places their activities in the "trading zone" that he has analyzed in depth elsewhere. Meanwhile, their peers in both disciplines are sometimes highly critical of their enterprise, whether because it fails to meet the standards of mathematical rigor or because it is not sufficiently constrained by empirical evidence. Thus, as Galison interprets it, the status of the objects, the identity of the investigators, and the values espoused by their respective disciplines are all in play at once and in intimately connected ways.

This shifting complex of objects, identities, and values appears to be characteristic as well for many other areas of contemporary science, some of which are discussed in this volume. They operate in the borderlands between one established discipline and another, using techniques that have yet to become fully naturalized. As a result, the reality of the objects they describe remains as uncertain as their own identities, whether the objects are fuzzy logic, the biological self, or artificial life.

Nonlinear dynamics and chaos

In a wide-ranging discussion of "Chaos, Disorder, and Mixing: A New Fin-de-Siècle Image of Science?" Amy Dahan captures some of the main historical developments in the mathematical and physical sciences that have upset traditional ideals and that many, both inside and outside the sciences, believe have given science a new face. Much of the action, once again, has occurred at the crossroads of the disciplines, joined there by computational exploration and the all-important computer as the engine of discovery for the modern world. Dahan is interested in how technical developments in many different areas have converged to produce the new *air du temps* of science. She is equally interested in how, during the course of this convergence, meanings have shifted. Chaos, for example, has for many centuries implied the antithesis of order, but through its mathematical and computational treatment in nonlinear dynamics and its experimental investigation in fields from cardiology to meteorology, order and disorder have come to be seen as intimately related. The same holds for randomness and nonrandomness, determinacy and nondeterminacy. Much current research focuses on this interdependence and on the subtle crossover between previously antithetical states, as epitomized in the now standard expression, "deterministic chaos." We may be authorized to speak once again of a dialectics of nature, but in a sense entirely different from that of the polar forces and higher syntheses of Schelling, Hegel, and other *Naturphilosophen* of the early nineteenth century. Not polarities but contingencies, not syntheses but hybrids populate the dialectics of complexity in the sciences of the late twentieth century.

The most obvious victim of complexity has been the reductionist ideal of explaining the properties of complex entities in terms of the properties of simple elementary entities. Not that anyone doubts that reductions can be carried out to yield successively molecules, atoms, nucleons, and quarks, but the reverse processes seem to defy any simple summation of parts. In the process of synthesis, symmetry breaking is often invoked, connecting the hierarchy of elementary particles with the phase transitions of condensed matter physics. More generally, one speaks of emergent properties, typically resulting from nonlinearity in the equations governing interactions. But most profoundly, as Dahan stresses, simplicity and complexity are no longer antithetical. Very simple systems, in mathematical terms, exhibit complexity, while complex ones exhibit simplicity.

Coupled with the surprising properties of simple systems has come a renewed interest in phenomena of everyday life. Not only clouds and ocean currents but dripping faucets and the forms of snowflakes have acquired an interest of their own, almost independent of the water molecules to which they once were supposedly reducible. It is the subtle dynamical processes responsible for these mundane phenomena in all of their irregular regularity that draws attention. And with that focus on dynamical processes comes also a renewed interest in the historical contingency of things. In slightly different circumstances they might look radically different. The task of scientists, Dahan observes, then becomes similar to that of every historian, to understand the processes of temporal development as they occur in the real world of variation and perturbation, where remarkable stability and order coexist with instability and disorder.

The roots of this shift in meanings and goals have been many and diverse. Nevertheless, to get at some of its characteristic mix of new mathematical practices with changing views of how the world is, David Aubin takes us back to "Forms of Explanation in the Catastrophe Theory of René Thom: Topology, Morphogenesis, and Structuralism." Catastrophe theory generated widespread enthusiasm in the late 1960s and early 1970s and has left an indelible mark on the vocabulary of complexity and nonlinear dynamics, despite its collapse in the late 1970s as a program for research.

As for so many later mathematical investigators (including string theorists) topology provided Thom's technical resource base. Although thoroughly trained in the formalist mathematical structuralism of the French group that named itself Bourbaki, Thom favored intuitive geometrical conceptions over rigorous proofs. Even as one of its most successful practitioners, he subverted the ethos of Bourbaki with his emphasis on shapes and their transformations. Morphological development of dynamical systems constituted the subject of catastrophe theory. The "catastrophes"—fold, cusp, swallowtail, and so forth—named the singularities that could occur in the transformations of a particular kind of topological objects, which Thom thought characteristic of natural systems. He sought the mathematical correlates, perhaps the mathematical reality, of the morphologies of the everyday world, like "the cracks in an old wall," arguing that naturally occurring shapes had primacy in themselves and should not be reduced to any more primitive elements. These shapes, he supposed, exhibited both a dynamical stability of structure and a set of possibilities for development that were governed by the topology they instantiated.

One of the most important sources for Thom's morphogenetic interpretation of nature, Aubin argues, derived from biology, particularly from embryological processes like cell division. A promising project was to interpret, in the intuitive topological terms of catastrophe theory, C. H. Waddington's earlier notion of an "epigenetic landscape" describing the relation between the genotype of an organism and the possible developmental pathways (valleys in the landscape) of its phenotype. Rejecting any reduction to molecular biology and focusing on the stability of the organism's final forms, Thom interpreted the branching points of valleys in the landscape as elementary catastrophes and he coined the term *attractor* to describe the state of dynamical stability of an organism in a valley or "basin of attraction." The terms have become ubiquitous in chaos theory even though Thom's belief in the generality of the elementary catastrophes and of dynamical stability has not held up.

As intriguing as the embryology-mathematics relation in catastrophe theory, Aubin explains, was Thom's attempt to reformulate the structuralist linguistics and social theory of the 1960s, if only heuristically, in the topological terms that he had extracted from Bourbakist structuralism. With this foray into semiotics Thom hoped to attain a theory of meaning itself. If his efforts ultimately undermined linguistic structuralism, as they had formalist mathematical structuralism, he nevertheless joined both enterprises in articulating an antireductionist view of knowledge that continues to resonate in the view that "reality presents itself to us as phenomena and shapes." The task of science, in this view, is to understand the dynamics of shapes, their formation and destruction.

Many investigators of nonlinear dynamics and chaos continue this morphological emphasis. But free of the faith in structural stability, which turned out not to be generalizable, and lacking Thom's commitment to qualitative analysis, they pursue quantitative mathematical and experimental investigations aimed at practical understanding and control of complexity. As Dahan has emphasized, this work occurs at the boundaries of order and disorder, determinacy and indeterminacy.

Coping with complexity in technology

The attention of nonlinear dynamics to complexity in the everyday world carries with it a close interaction between the mathematical sciences and engineering. But nonlinearity is not the only locus of complexity nor the only one in which engineers have played a leading role. This volume offers examples in two other widely divergent areas: finite element analysis and fuzzy logic.

Finite element analysis (FEA) is a technique of structural analysis that many engineering students today, using prepackaged computer programs, have encountered by their second year. The programs take a proposed structure as input and produce a stress-strain analysis as output, with little independent action on the part of the user, much as calculators have replaced long division. But it was not always so. Ann Johnson investigates the circumstances of the development of FEA in "From Boeing to Berkeley: Civil Engineers, the Cold War, and the Origins of Finite Element Analysis." She draws our attention to the fact that, as in so many other areas of complexity, it has been a combination of military requirements, industrial opportunity, and academic interest that has provided the motivation and funding for this computationally sophisticated but user-friendly vehicle of analysis.

In the Cold War environment of the 1950s, FEA addressed the problems presented by developing airframes for jet aircraft. They demanded maximum strength with minimum weight. Their costly construction made destructive testing of alternate designs unattractive, however, while the perceived need for Cold War advantage made increased speed in moving from design to prototype a critical consideration. For all of these reasons, Johnson explains, companies like Boeing sought better ways to model the performance of their designs prior to any material embodiment of them and prior to experimental testing in a wind tunnel. Accurate calculations of the strains that the airframe would experience under the loading conditions of jet engines and high speed would solve the problem, but existing means of structural analysis lacked the required accuracy.

The situation presented an opportunity for academic civil engineers, a group that had largely been excluded from the rewards in funding and prestige of what Eisenhower dubbed the "military-industrial complex." Johnson narrates how Ray Clough, a young Berkeley engineer with a summer position at Boeing, took up the challenge in 1952. In cooperation with his supervisor at Boeing, Clough identified the skin of an airplane as a critical structural element and found ways to model it through what he would soon name "finite element analysis." The procedure begins by dividing up a structure, such as the skin of a wing, into small elements forming a mesh, finer in critical areas and coarser in others. Applying linear equations of elasticity to each element generates a large set of simultaneous equations. The strain in the whole wing can then be calculated using matrix methods on a computer, effectively matching elements across their boundaries to build up an accurate simulation of the wing's response.

Johnson discusses three features of this method that are of interest here. First, the complexity that engineers refer to in the finite element calculation enters in the first instance through the practical requirement of accuracy in modeling and only secondarily through the physical nonlinearity of the problem, although underlying nonlinearity strongly affects the form and density of an adequate mesh. To put it differently, the method leads to an understanding of physical complexity through the complexity of the mesh and its associated calculation. Second, the technique would have been intractable for all but very simple structures without the digital computers that IBM leased to Boeing and a small number of other aerospace companies but that were not originally available in academia. These two features involve a third: the priority placed on accuracy and computing power correlates with a notable shift in engineering values, from mathematical elegance to utility in modeling.

Dahan also points out this instrumentalist orientation, which seems to arise quite generally in the shift of values from simplicity to complexity and unity to diversity, since it involves a widespread turn to understanding and controlling the strange properties of mundane things through computational means. In common parlance, the computations proceed "from the bottom up," beginning from a specification of rather simple actions or interactions of some operative units. The units may be natural (electrons) or artificial (finite elements), with the latter often obtained by conceiving the problem as a grid, patchwork, or network. Then the computer program simulates the behavior of the entire system by performing the actions and interactions of the units, typically in a stepwise fashion through the continued repetition of a set of algorithms. The procedure thus grows the behavior of the system as a whole, often revealing emergent properties that could not be predicted from the behavior of the parts, especially when the interactions are nonlinear. Ironically, although this emergent holism is often regarded by its critics as romantic, it is equally open to their charge of mere instrumentalism because its primary criterion of validity is accuracy of simulation. As a historical matter, we should no doubt attribute the conflict to the shifting sands of "simplicity," "elegance," and "fundamentality."

That those sands are shifting can be seen also in a means of coping with complexity very different from FEA, namely, fuzzy logic. It too mixes its validity as a description of how the world is with its utility in controlling technological devices, now made more user friendly by fuzzy logic. In "Fuzzyfying the World: Social Practices of Showing the Properties of Fuzzy Logic," Claude Rosental examines how its proponents have spread their message through various modes of "showing." These heterogeneous modes might normally be called "proofs," "histories," and "machines," but Rosental is concerned with how they are used in concert to make the virtues and properties of fuzzy logic seem manifest. He therefore describes their function as that of mediators, mediators which themselves disappear in the course of "showing," or making immediately visible, the power of fuzzy logic.

Fuzzy logic operates on the premise that statements about the world are not simply true or false but have a continuous range of truth values, so that a statement and its contradiction may both be partly true. Showing how a famous contradiction or paradox in binary logic gets resolved in a natural way by fuzzy logic therefore provides an effective strategy for proponents. Rosental observes that its effectiveness depends not only on abstract reasoning but also on its staging through a series of familiarizing manipulations and translations that are displayed materially as inscriptions on a page. The reader is supposed to experience the proof visually through its performance. Its manifest credibility can then be appropriated into other means for establishing the universal status of fuzzy logic, such as a cultural history that shows the demise of Western binary logic in self-contradictions and the rise of Eastern thinking in continuous-valued logic. Detractors, of course, mount their own performances to depict the proofs as deceptive and fuzzy logic as nothing fundamental, offering no properties that traditional logics cannot provide. The stakes in the contest are high; besides intellectual rewards, they include funding from industrial and military sources for academics and sales of control mechanisms for design companies and manufacturers.

Among the most interesting mediators of showing that Rosental discusses in this context are “demos” of consumer products like cameras and vacuum cleaners. Such demos have been the most important means of promoting fuzzy logic in both academic and business settings. For that purpose, a demo depends on a skillful demonstrator who acts as the representative of a device in operation and exhibits its properties as embodied properties of fuzzy logic. Success, Rosental argues, depends first on making the properties of fuzzy logic emanate from the device as its epitome (while effacing many other components and properties) and then on detaching them from the device as transcendent properties available for reasoning in other contexts, as well as for other control mechanisms of many kinds. Not only must the particular device disappear; the demonstrator too must become immaterial to the demonstration.

Rosental’s analysis thus delves into the mechanisms through which unfamiliar aspects of complexity may become naturalized in the world by interrelating truth and utility, or specifically here, truth value and use value. More globally, it makes explicit how such a project of naturalization may incorporate a thorough rewriting of intellectual and social history.

Part II. The organism, the self, and (artificial) life

Just as the physical sciences have been reevaluating in the last several decades the ways in which they formerly ascribed priority to particle physics as “fundamental physics,” and even within that domain the new units called strings are neither so intuitively elementary nor particle-like, so in the biological sciences, the former citadel of reduction to elementary genes, molecular biology, has been finding that "the gene" is not so easily localizable and that its relation to phenotypic traits is complex indeed. In the broad fields of biology and medicine beyond the molecular domain, complexity is even more apparent. It is with those broader fields in view that the essays in Part II reflect on questions so basic to biology and medicine: What is an organism? What, speaking immunologically, is the self? And what is life? These are all questions with long histories that have found new formulations in contemporary research, particularly with respect to both actual and metaphorical uses of the computer and with respect to the problem of self-organization.

Self-organization

To introduce the contemporary scene in historical perspective, Evelyn Fox Keller discusses "Marrying the Premodern to the Postmodern: Computers and Organisms after World War II." She succinctly recovers some of the main episodes in the rising and falling fortunes of self-organization over the last two hundred years. As in much else, Immanuel Kant set out with particular clarity the concept of an autonomous entity in which every part is both end and means in relation to the other parts. Highly developed as a nonvitalist research tradition in the first half of the nineteenth century (dubbed "teleomechanism" by Timothy Lenoir),[5] the Kantian agenda declined in the second half of the century with the rise of more strictly mechanist physiology and then with genetics, although variations on the theme survived in areas like embryology, where questions of the internal dynamics of development remained crucial.

In the United States especially, the Morgan school of genetics reigned supreme by the 1930s. They and their successor molecular geneticists even claimed to rule embryology itself. The discovery of the double-helical structure of DNA in the early 1950s seemed to confirm that self-replication and development would soon be reduced to the mechanics of particle-like genes. Meanwhile, something quite different was going on. The problem of aiming the antiaircraft guns of World War II gave rise to "cybernetics." Innocent of molecular biology but schooled in the mathematics and engineering of feedback mechanisms, the promoters of this new science envisaged self-controlled, goal-seeking machines with digital computers at their heart. To articulate this vision, Keller has shown, they adopted the older biological language of self-organization and organicism that the molecular biologists were expunging from biology itself.

It remains one of those fascinating "accidents" of history that cybernetics, though it prospered for twenty years after the war, enrolling biologists with a bent for embryogenesis and pioneering connection machines and neural nets, had virtually died out by 1970, the apparent victim, on the one hand, of its own lack of tangible success, and on the other, of the remarkable successes of sometimes stridently antiorganicist research strategies in both molecular biology and computer science. Equally fascinating is its rebirth in new forms in the last ten to fifteen years. The history of this period is only now being written—indeed, being made—but two features seem apparent. First, molecular biology itself has become much more complex. Despite the continued promotion, especially in popular writing, of the myth of a simple one-to-one relation between genes and phenes—one gene, one protein—detailed research has made it increasingly difficult to maintain this central tenet of the older molecular faith. At every level, from DNA sequences to transcription into RNAs to translation into proteins, the notion of the singular gene with its unique product has become untenable. Even which sections of DNA are to count as genes is made problematic by the fact that the vast majority of sections do not code for proteins but serve a myriad of regulatory and other functions, mostly unknown, so that any given product results from a complex web of interactions at various stages involving many different sections of DNA. Similarly, a great deal of cutting and pasting of pieces has been shown to occur at the level of transcription, such that one sequence can ultimately give rise to many different products. And translation may be no simpler, with a variety of modifications being required to convert an original translation product into its functional counterpart. Summarizing this situation, the historian Hans-Jörg Rheinberger has remarked: “It has become evident that the genome is a dynamic body of ancestrally tinkered pieces and forms of iteration.”[6] As he interprets it, this new organicism results quite naturally from the increasingly complex experimental systems that are producing the future of molecular biology. Nevertheless, it has brought with it attempts to reincorporate the older cybernetic vision.

That attempt, as Keller observes, involves a second and most obvious feature of the changed conceptual landscape, the computer. The personal computer has brought complexity down to earth, within the purview of all those whose work it performs and whose lives it interconnects with such immediacy. And atop this everyday functionality is built the broad spectrum of computer-based fields encompassed under names like nonlinear dynamics, computational biology, and cognitive science. Everyone now wants to know how to think about complex systems and how to work with them. Biological systems are the Holy Grail.

Among various proposals for reconceptualizing biological complexity, or the organism, one of very general scope has been articulated by Humberto Maturana and Francisco Varela under the name of *autopoiesis.* Keller observes, in fact, that they drew inspiration for their theory directly from participants in the old cybernetics. The rebirth, however, has a much expanded domain for action. The other authors in part II have taken up two such areas, which are exemplary for both the promise and the problems of making sense of the biological "self" and of "life." They are immunology and artificial life.

Immunology

The problem of the self, in philosophical terms, has been the problem of identity: In what sense, and how, does an individual remain the same individual over a lifetime of constantly changing material and mental existence? In the biological domain, the self lies in the territory of immunologists, but in a very special sense. Throughout the twentieth century they have been attempting to understand how the immune system acquires the capacity to distinguish the agents that perform the normal repertoire of bodily functions from the agents that disrupt those functions, or self from nonself. The dominant metaphors for describing this relation between self and nonself have been invasion and war, invasion of antigenic foreign agents and the war against them carried on by a domestic defense system that somehow recognizes otherness and deploys such weapons as a specialized army of white blood cells, the T4 lymphocytes. But the immune system is notoriously complicated and alongside the images of war have always stood alternative pictures in which the self represents the relatively constant properties of a shifting network of interactions. Self and nonself, in such views, are part of the same process of recognition, so that what counts as the one or the other depends on context. The proving ground for these alternatives has been autoimmunity, in which the system seems to turn on itself and attack its own agents. Is autoimmunity simply an extreme of the normal process of recognition, a symptom of the dynamic system having lost its self-generating stability? Or is it the pathological behavior of a system gone completely awry?

In "Immunology and the Enigma of Selfhood," Alfred I. Tauber advocates a complex-systems view. He believes immunology has outlived the reified self, with its fixed boundary between self and nonself. In its place he would put a dynamic, process-oriented description of a system whose continuing growth, in constant interaction with both its inner and outer environment, yields the emergent properties commonly associated with the self. Tauber writes in a highly personal vein, exceeding the usual conventions of either history or science. But he believes that the reified self is a holdover from a "modernist" ideology and that his own trajectory in coming to a "postmodern" view, while surely atypical, may nevertheless represent trends that have been developing since the 1970s, when Niels Jerne presented his "idiotypic network theory" of the immune system as a contrast to the "clonal selection theory" of Macfarlane Burnet dominant in the 1950s. Other important resources for Tauber have been the perspectives of Francisco Varela (although he is critical of the autopoiesis interpretation per se), Antonio Coutinho, and others analyzing the immune system as analogous to the nervous system and to language. This work has sometimes been done at the Santa Fe Institute, where so much of complex-systems analysis has germinated. Tauber began, however, from the early history of immunology and from a historical reinterpretation of the works of Nobelist Elie Metchnikoff, whose import, he argues, has been obscured within the modernist tradition.

An empirically minded historian who doubts immunologists have much enthusiasm at present for a complex-systems approach is Ilana Löwy. In "Immunology and AIDS: Growing Explanations and Developing Instruments," she takes a practical approach to evaluating competing views of autoimmunity by looking at the most famous case of it. She shows that in the early history of the disease clinicians observing the response of patients to infection with HIV (human immunodeficiency virus) and their subsequent development of full-blown AIDS (acquired immunodeficiency syndrome) leaned toward the complex-network approach, especially because the viral load in the bloodstream of infected patients seemed to be very low, far too low to support the image of warfare between virus and T4 cells. And yet, as patients developed AIDS, their T4 cell counts plummeted, suggesting that the immune system had lost control of its stabilizing dynamics and was destroying its own defenses. The T4 cell count thus seemed to be the best marker of the disease's progression, as a disease of autoimmunity. From about 1990, however, new technologies for detecting the virus became available. They revealed not only much higher levels of HIV in the blood of AIDS patients than had previously been thought but also that during the prior period of supposed dormancy the virus was actually multiplying rapidly in the lymph glands, out of sight of the earlier tests. As the new tests gained precision and reliability, the warfare image quickly resurfaced as the dominant explanation of infection. The war going on in the lymph glands was depleting the T4 cells in the blood. With that, the disease reentered more conventional virology as an infectious disease, with viral load as its measure, and the previous emphasis on the mechanisms of disruption of the immune system disappeared.

This is a cautionary tale. It may very well be, Löwy agrees, that the immune system—and with it the biological self—will ultimately require for their adequate understanding the concepts and tools of complexity theory, but in the particular case of AIDS, the disease can best be diagnosed and represented as an all-out viral attack that ultimately overwhelms the immune system's capacity for defense. This conception, moreover, has major implications for treatment. Drugs that kill the virus directly are, at present, the only effective agents. This practical lesson carried by the instruments of diagnosis and treatment stands in uneasy relation with the complexities of discriminating between the self and nonself and the ephemeral status of the postmodern self.

Artificial life

At the very edge of the real in the age of complex systems stands artificial life. How can this life be narrated? What are the rhetorical resources that artificial life researchers join with the digital computer in projecting life into the little "animals" that populate the screen? And how might life be defined? These are the questions taken up by literary critic Richard Doyle, anthropologist Stefan Helmreich, and biologist Claus Emmeche.

Alife makes Richard Doyle nervous, as he says in "Artificial Life Support: Some Nodes in the Alife Ribotype." He would like to understand how the little creatures of Alife come to seem lively—at least to some observers—and narratable as organisms moving through space and time. Why would anyone imagine that a pattern of flashing lights on a screen, representing visually the states of a Boolean network as widely distributed as one cares to imagine, have anything to do with life? Adopting an analogy from theoretical biology, Doyle argues that just as the translation of genotypes into phenotypes has been said to depend on an intermediary set of "ribotypes" that translate the information encoded in DNA (genotype) into the functional proteins and higher-order structures of a living organism (phenotype), so the translation of digital states into lifelike virtual creatures in Alife depends on a complex of translational mechanisms or rhetorical ribotypes. The rhetoric of localization, for example, produces the intuition that something inside the computer is alive, while that of ubiquity makes it seem that almost anything could be alive.

To explore these modes of actualization more deeply, Doyle employs C. S. Peirce's notion of "abduction." Abduction is the method of projecting into the future the realization of a present expectation or hypothesis. It allows a novel concept or subject, a new unity, to stand in the place of an otherwise disconnected set of predicates. Doyle shows how the rhetoric of Alife uses a form of abduction to project "life-as-it-could-be" into the open future of life as simulacrum, not simply a simulation of biological life but a creation by simulation of life in silicon. But producing this "life effect" depends also on the sheer contingency and unexpectedness of what befalls the creatures of Alife because their generation from nonlinear and evolving algorithms precludes the possibility of knowing their fate in advance. They must be run or grown. Furthermore, their survival depends on their interaction with the humans who help to narrate their life and thereby continue the process of its abduction.

These issues of narrative effects and their problems are familiar territory for literary critics. Doyle finds fruitful analogies in the writings of Philip K. Dick. He also finds useful, as do so many others attempting to come to grips with complexity, the concept of autopoiesis as developed by Maturana and Varela. Autopoiesis might provide the autonomy and interiority of the living organism that initially seems so lacking in the distributed networks of Alife.

Stefan Helmreich is also concerned with how Alife converts the virtual into the actual, but in “The Word for World Is Computer: Simulating Second Natures in Artificial Life” he investigates the transformation through an ethnography of Alife researchers, basing his analysis on fieldwork at the Santa Fe Institute in New Mexico. He has explored the cultural resources they invoke to render computer simulations as “worlds” or “second natures,” maintaining that the transubstantiation depends on conjoining familiar mythologies of European and American culture with computer science and complex-systems theory. Such a world, however, is not merely a dream world. It depends on the reasoned view that the sets of machine instructions making up the self-replicating creatures in a simulation are the same sort of thing as the amino acids that make up a biological genome. More generally, it depends on the controversial view that our familiar world is just a mammoth computer that continuously generates and carries out its own complex instructions. This view is grounded formally in the physical Church-Turing thesis, claiming that any physical process can be thought of as a computation. So for those who accept the strong claim, the artificial world inside the computer is indeed a real world, however different from the usual one.

Still, the artificial world gains much of its intuitive reality from its assimilation to everyday cultural myths and metaphors by Alife researchers. The “green” and natural organic world of ordered processes developing in evolutionary progression is one such metaphorical resource. Another calls on the creation stories of Judeo-Christian theology to put the Alife programmer in the role of a deistic god who creates the world and its laws, which then run on their own until the god destroys them. Similarly prominent in informal discussions among Alifers, Helmreich shows, are science fiction stories of travels in cyberspace, frontier imagery, and colonization. Many of these stories involve a thoroughly masculine discourse of creation, exploration, and conquest. The effectiveness of the imagery, however, depends always on the very lifelike simulations made visually present on the screen, as though seen through the glass of an aquarium.

If Doyle and Helmreich make us aware of the narrative and cultural conventions on which Alife relies and of how important those resources are to its liveliness, Claus Emmeche attempts to unpack more formally the implicit conceptions of life that may lend theoretical coherence to its claims. In "Constructing and Explaining Emergence in Artificial Life: On Paradigms, Ontodefinitions, and General Knowledge in Biology," he draws from biology two possible definitions of life, which he calls "ontodefinitions" to emphasize their status as root metaphors for the sorts of things that can count as living. These he calls "life as the natural selection of replicators" and "life as an autopoietic system." They both treat life as an emergent phenomenon but in different senses.

The first view—that life can be regarded as a property of entities that self-replicate by a process of information transfer and that evolve by random variation and environmental selection—seems to be widespread among biologists, although largely as an implicit assumption rather than a definition. Emmeche makes it explicit, emphasizing an important distinction between the mere self-replication of information by a computer program and the full self-reproduction going on in cells, which is carried out by self-maintaining material and causal processes in the cell. Whether the silicon-based replication in computer simulations can be regarded as "real" self-reproduction may be the central debating point for Alife.

Focusing on this autonomy of the cell, the same interiority to which Doyle refers, leads Emmeche also to the theory of autopoiesis as presented by Maturana and Varela and to his second ontodefinition: life as an autopoietic system. In this scheme, which is as yet entertained by only a small minority of biologists, the metabolic processes in a cell constitute an organizationally closed network of self-reference which produces itself and its own components, as well as its boundary, while drawing energy and materials from its surroundings. In this self-referencing character of the biological network lies the emergence of biological life from physical mechanism. The theory, however, does not provide a physicochemical analysis of the structure of the network. Rather, it offers an account of the characteristics of a network that could be called autopoietic and therefore autonomous. Likewise, questions of reproduction and evolution are secondary. But the theory is general enough to include autopoiesis in the virtual space of a computer as well as in physical space and therefore may be of increasing interest as the simulations of Alife become ever more realistic.

First, however, Emmeche believes we need a better understanding of key notions, beginning with emergence. To this end he presents an analysis by Nils Baas. Baas's view is of interest because it incorporates explicitly the role of an observer as a necessary ingredient for a particularly strong form of emergence, that in which the properties of a complex system are not simply computable from known interactions. The "observer" need not be a living agent but may be simply the environment with which the system interacts (reminiscent of the role of observation in quantum mechanics in producing distinct states of momentum or position). When humans are involved, however, readers will want to recall Doyle's concern with the role of observers in the continuing narration of Alife creatures, their survival and evolution.

Conclusion

It would be impossible to capture in a few sentences the changing character of scientific explanation in the last several decades. The essays in this volume seek rather to explore some of the diverse strands of that change and to present them in a readable form. Although they cross the broad spectrum from strings to Alife, however, they do exhibit some representative features. Repeatedly we find objects understood as dynamical processes rather than static units, objects defined by their topological or morphological properties. They seem to be best understood in terms of self-stabilizing systems whose properties can sometimes be captured by simulating them on high-speed computers. In this generative computational effort, the bottom-up approach to explanation has come into its own. It gives concrete substance to the notion of growing explanations, perhaps heralding a sweeping transformation of the reductionist program that has dominated scientific explanation in the modern period. Instead of particles all the way down, it would be dynamics all the way up. That scenario, however, remains very much in flux. It continues to arouse the uncertainties, and often the passions, of people both inside and outside the specialized sciences. And it involves a great deal of boundary crossing between those specialities. These features make the history of contemporary science an ideal location for viewing the intimate relationship between the content and goals of the sciences as well as the identities and values of their practitioners.

Notes

1 Details available through the websites of "Physics First" and "ARISE" (American Renaissance in Science Education); Tamar Lewin, "A Push to Reorder Sciences Puts Physics First," *New York Times*, January 24, 1999, 1; representative response letters, January 27, A24; Marjorie G. Bardeen and Leon M. Lederman, "Coherence in Science Education," *Science*, 281 (1998), 178–79; Leon Lederman with Dick Teresi, *The God Particle: If the Universe Is the Answer, What Is the Question?* (Boston: Houghton Mifflin, 1993).

2 A more radical philosophical suggestion, called “metaphysical pluralism,” would be that the higher levels constrain the lower ones as much as the reverse and should be regarded as independent; to make the building-up problem fundamental is simply to maintain the old metaphysics of reduction in a new form, called “supervenience.” See Nancy Cartwright, *The Dappled World: A Study of the Boundaries of Science* (Cambridge: Cambridge University Press, 1999), especially “Fundamentalism versus the Patchwork of Laws,” 23–34.

3 Nicholas Wade, “Life is Pared to Basics; Complex Issues Arise,” *New York Times*, 14 December 1999, F3; Clyde A. Hutchison III et al., “Global Transposon Mutagenesis and a Minimal Mycoplasma Genome,” *Science* 286 (1999), 2165.

4 Mildred K. Cho, David Magnus, Arthur L. Caplan, Daniel McGee, and Ethics of Genomics Group, “Ethical Considerations in Synthesizing a Minimal Genome,” *Science* 286 (1999), 2087–2090.

5 Timothy Lenoir, *The Strategy of Life: Teleology and Mechanics in Nineteenth Century German Biology* (Dordrecht: Reidel, 1982).

6 Hans-Jörg Rheinberger, “Gene Concepts: Fragments from the Perspective of Molecular Biology,” in P. J. Buerton, R. Falk, and H.-J. Rheinberger, *The Concept of the Gene in Development and Evolution: Historical and Epistemological Perspectives* (Cambridge: Cambridge University Press, 2000), 219–239.