Articles

BEAUTY IN THE LIVING WORLD

by Alejandro Garcia-Rivera, Mark Graves, and Carl Neumann

Abstract. Almost all admit that there is beauty in the natural world. Many suspect that such beauty is more than an adornment of nature. Few in our contemporary world suggest that this beauty is an empirical principle of the natural world itself and instead relegate beauty to the eye and mind of the beholder. Guided by theological and scientific insight, the authors propose that such exclusion is no longer tenable, at least in the data of modern biology and in our view of the natural world in general. More important, we believe an empirical aesthetics exists that can help guide experimental design and development of computational models in biology. Moreover, because theology and science can both contribute toward and equally profit from such an aesthetics, we propose that this empirical aesthetics provides the foundation for a living synergy between theology and science.

Keywords: aesthetics; Christopher Alexander; computational models; developmental biology; empirical aesthetics; experimental design; pattern formation in developing tissues; theological aesthetics

INTRODUCTION: BEAUTY AS SCIENTIFIC GUIDE

The issue of an empirical aesthetics may be placed in the form of a question: Can the recognition of beauty be of practical use for guiding experiments and model building in science?

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We argue here that beauty is not only a subjective response in the eye of the beholder but also an objective property of natural systems. That property must then be amenable to empirical observation and definition. Moreover, if beauty is an objective property of natural systems, aesthetics is necessary for anyone attempting to fully understand such a system. To demonstrate this point we use the example of a well-known scientific breakthrough in the field of developmental biology.

Unlike most experimental scientists, mathematicians freely admit to deriving aesthetic pleasure from their work and are not averse to describing mathematics as beautiful. In the words of Bertrand Russell, "Mathematics, rightly viewed, possesses not only truth, but supreme beauty" (1918, chap. 4). Indeed, the *elegance* of a mathematical proof often is used to support its validity. The elegance of a proof can be attributed to several properties, including simplicity, internal consistency, originality, and the ability to generalize it to other problems. Conversely, a result that is logically correct but that depends on many complex assumptions, or that cannot be generalized, is often described as *ugly* and is rejected in favor of more elegant solutions.

Moreover, this claim has important implications for the science-and-theology dialogue. An apt analogy that opens the doors of science to theology is the suggestion by various scientists that beauty is connected to the unknown, that is, those aspects of the system that are not fully understood. The theologian can see the notion of mystery as analogous to how the scientist understands the unknown. Just as beauty helps the theologian navigate an understanding of divine mystery, beauty can help the scientist navigate the natural unknown. Thus an appreciation of natural beauty and knowledge of her rules, that is, an aesthetics, would be a great asset to any scientist, because science always aims to go beyond the known. The important connection that beauty makes between theology and science ought therefore to be emphasized more.

For the theologian, natural beauty may be the key in helping theology understand God's divine action in the world. If Newton's view of the universe was responsible for the exclusion of beauty from empirical data, this was probably the result of the prevalent view in his time that divine action consisted mainly in terms of God's absolute power (*potentia Dei absoluta*). Thus, Newton visualized a universe consisting of absolute space and absolute time coordinates. Left out in such a view is divine action as an expression of God's ordaining power (*potentia Dei ordinata*).[1] If God's ordaining power is accounted for in a theology of Nature, the demonstration of an empirical aesthetics of natural beauty can be seen as a manifestation of God's immanence in the world. This rethinking of God's immanence is theology's gift to the natural sciences, for it suggests that beauty is at the heart of ultimate reality itself.

More important, theology's suggestion that beauty is at the heart of ultimate reality enters a philosophical and, ultimately, empirical debate raised by the data of the biological sciences, especially the science of molecular biology. This debate finds its sharpest form in the rising field of philosophy of biology.[2] Philosophy of biology addresses many problems in the philosophy of science, but one of its most active inquiries concerns the reductionism inherent in seeing biological organisms as mere special cases of physical systems. The problem can be seen clearly in this comment by molecular biologists J. Cohen and S. H. Rice:

> Molecular biology has set itself the task of looking for the fundamental pieces with which the biological jigsaw is to be put together. Not surprisingly (but with surprising efficacy), it has found many of them, and there are certainly more to come. Once found, these pieces can be arranged on a page next to one another in a reasonable sequence, and . . . Behold! An organism! Well, not quite. (Quoted in Robert 2007, 361)

This "not quite" reveals the weakness of the reigning scientific epistemology that holds that knowing the parts is sufficient explanation of the whole. It is becoming increasingly clear that this epistemological paradigm is in deep trouble when it comes to understanding biological systems. It is not a new issue in philosophy (Nagel 1979, 398ff.). Nineteenth-century biologists struggled with vitalism and philosophies of organism as proposals that were supposed to answer the epistemological conundrum. The spectacular successes of molecular biology of the twentieth century revealed these epistemological proposals to be inadequate. An epistemology based on the whole does not seem as yet to be able to compete with an epistemology based on the parts. On the other hand, an epistemology of the parts does not do justice to the biological phenomenon that is a systemic whole.

This epistemological tension crosses over into the criterion of judgment and the creative instinct that resides in the subjectivity of the investigating scientist. Preliminary results obtained from interviews with biologists suggest that scientists experience a deep conflict between appreciating the beauty of a system they seek to understand and feeling compelled to take apart the system to produce knowledge that can be used to manipulate and exploit the system.[3] A theological aesthetics addresses both the deep conflict experienced by the scientists and a possible resolution of the conflict by suggesting a way in which the tension can not only be appreciated but also lead to significant experimental results.

How do scientists overcome this obstacle, and how do they deal with this tension? With the new discoveries occurring in the field of biology, the question of the ambivalence of the "what" of scientific knowledge is being asked anew. This is nowhere more striking than in the rising field of systems biology, which aims to describe entire living systems (such as cells, organs, and whole organisms) in their totality, such that insights about the parts of these systems are always embedded in an understanding of the whole. This aim depends on two distinct approaches. The first is based on taking apart the system to analyze the parts; the second is based on putting the parts together to understand the whole. These distinct aims generate a tension that is further increased by the fact that any system arising out of synergistic interactions between its parts exhibits emergent properties that cannot be predicted by analyzing the parts in isolation. To overcome this tension, systems biology tries to integrate the results of diverse experimental approaches: analytical experiments (such as biochemical analysis), synthetic experiments (such as computational modeling), and more recently imaging experiments (such as time-lapse photography of living cells).

Systems biologists find that integrating these distinct methodological approaches is challenging. "Modelers" believe that scientific knowledge lies in the modeling of Nature. They believe they "know" something about Nature if their models reveal the parameters that control the behavior of the natural reality they are studying. "Imagers" believe they actually know something about the natural reality they study by watching its behavior. "Modelers" claim that "imaging" experiments are purely descriptive and give us little knowledge at all. Scientific knowledge is real if it leads to control of the reality studied. "Imagers" point to their great success at discovery. Through their time-lapse photography they have made major discoveries in developing biological systems.

We suggest that this sense of unease about the adequacy of the reigning paradigm of scientific method lies in an intrinsic ambiguity found in the question: What does science know? The ambiguity is found in the *what* of the question. Does the *what* refer to the theories that science knows or to the *what* of the reality it studies? Does scientific knowledge consist of theories, maps to the reality it studies, or does it consist of the territory, and the actual reality it studies? It was Galileo's genius that created the ambivalence, for in connecting reason to experiment and reasoning about Nature with control over Nature Galileo blurred the lines between map and territory.

We believe that the issue may be more fruitfully investigated if beauty is recognized as a empirically accessible category.[4] The proposal comes from an understanding of the oldest definition of beauty as unity-in-variety (Tatarkiewicz 1980, 121–52). Beauty refers not merely to the whole or the parts but to that mysterious unity that the parts have with the whole. As such, a study of what makes an organism beautiful does not entail an epistemology based on the whole or one based on the parts but, rather, an aesthetics—the discovery of the rules or principles whereby parts find a unity in the whole. When applied to biological organisms, this definition reveals how inadequate contemporary philosophical aesthetics has been when it comes to understanding natural beauty.

Such an aesthetics emphasizes an objective dimension in natural beauty. Belief in the objectivity of beauty, however, has declined precipitously in the secular academy. Indeed, the belief that there is such as a thing as Beauty has been hotly contested in contemporary philosophical aesthetics. Much of this decline can be laid at the feet of a rival aesthetics worked out during the Enlightenment. This aesthetics, known as the Grand Narrative, sees the experience of beauty as “disinterested, perceptual contemplation.” Disinterested, perceptual contemplation eschews the senses in favor of the mind (the mind, that is, as understood in eighteenth- and nineteenth-century epistemologies). As such, the objective dimension of Beauty and its empirical dimension is made problematic. It makes the experience of beauty, namely the beautiful, a product of the mind rather than an experience obtained through the senses and interpreted by the mind.

If philosophical aesthetics has acted to subjectivize the experience of beauty, some scientists have acted to exclude any subjectivity from being relevant to natural phenomena. Jacques Monod’s popular book *Chance and Necessity* (1972) introduced language and a worldview that, in our estimation, has worked to stifle our understanding of biology. Monod, working out of the French intellectual tradition—the philosophical tradition founded by René Descartes—proposed an anti-Cartesian proposition: There is no *res cogitans*, only *res extensa*. He did this by claiming that biology was a special case of physics. The subject of physics, matter, was also the subject of biology. Biology, Monod conceded, was a special and rare case in the vast universe of matter. Thus, he shifted the subject of biology. The subject of biology would be not life but matter. Monod did this to make sure that no vitalism—the idea that life has a different principle than physical matter—would contaminate biological thought.

Monod thereby introduced a certain blind spot in current biological thought. He would have scientists read biological reality as mere data instead of phenomena—that is, as concepts stripped of perception. This means that the book of Nature is a story told with mere data just as a manual tells its story. This has led many scientists to wonder if they are reading the book correctly. These scientists wonder, as Henry David Thoreau once wondered: “What sort of science is that which enriches the understanding but robs the imagination?” (1906, 155–56)

By objective Beauty in a contemporary scientific context we refer to patterns of information immanent in natural phenomena. A person experiences beauty through the senses and mental interpretations, and some natural phenomena have intrinsic relationships whose rich and informative simplicity more easily lead to an experience of the beautiful. Discovering the truth in science and the beauty in nature correspond when the relationships within natural systems have a form free from internal inconsistencies and amenable to simple and elegant theoretical modeling.

Of course, nature does not always have a simple and elegant beauty. The power within nature can appear ugly and even cruel to some sensibilities, but we focus here on systems where evolutionary pressures and other repeated natural constraints have resulted in beautiful forms. In the field of developmental biology, the unfolding of biological structures during embryo development includes many processes that we claim have an objective and empirical beauty.

ALEXANDER'S EMPIRICAL AESTHETICS

In order for beauty to have empirical meaning to science, it must be clearly defined as a property of dynamic systems arising in time and space. Moreover, the recognition of beauty in such systems must be guided by an aesthetics with a strong empirical basis. To address this requirement, we adapt here the work of architect Christopher Alexander, who has proposed a formal theory of empirical aesthetics. In his aesthetics Alexander offers another important definition of beauty: it is "freedom from internal contradiction" (1979, 26). This definition is highly useful for scientists because freedom from internal contradiction can be used as an excellent criterion to judge the validity of experimental results, ad hoc hypotheses, and formal models.

In the work of Alexander we find a rich theory of aesthetics that proposes life as an aesthetic category. In a series of brilliant books he discusses his unhappiness with an architectural worldview that sees buildings as ordered assemblies of parts. He finds that such a view of buildings does little justice to the nature of the space created for human life. Indeed, he observes that architectural space is also space that sustains and promotes life, indeed gives life. As such, the metaphor of assembly does not do justice to the art of architecture.

Alexander notes that the language of assembly does not take into account human feelings or desires in the space created. The *I* of human subjectivity must be one with the *it* of architectural material structure. This naturally suggests a metaphor of living structure. This living structure, Alexander concludes, must be an environment of living centers that resemble the human *I* that will inhabit and take root in them.

> First, that the core of the issue, the core of the architectural issue, was the extent to which people's inner feelings and desires—their reality—could interact with buildings. This topic ignored, and rendered almost horrible in the disdain and supercilious know it all of contemporary architects, was vital and quite horrible. The simple proposition that all this has to do with the extent that people feel rooted in the world, was paramount. Second, that a well place, a healing environment, a house, or a room, or a village, or a major urban street, are valuable, only to the extent that this environment is made of living centers which resemble, and remind us of the person's own self. Thus in a healthy structure, we have a structure (in a city street, say, or in a window sill) which is like the hundred million buddhas or angels, all crowding into space. This not used as a metaphor, but as a nearly literal description of the condition in space when the density and packing of living centers in a structure is profound. This was startling, and a revelation. (Alexander 2007, 6)

This revelation led Alexander to take on the language of living organisms. He proposes a far better metaphor for the design of buildings: unfolding. Architectural space is space that unfolds. It unfolds into a space that becomes a living center where the subjectivity of the *I* interacts with the objectivity of the structure forming a dynamism that is experienced as life. Indeed, he makes this his aesthetic category. The beautiful, he proposes, is measured by the degree of life experienced in inhabiting the space formed by the structure. The relation between structure and life is governed by centers that shape structures according to fifteen aesthetic principles that give rise to a structure shaping a space that is "free of inner contradiction." What makes Alexander's aesthetics so powerful is that he documents and uses it successfully in his own architectural practice.

In his theory of aesthetics, Alexander defines fifteen fundamental properties of spatial organization significant for the beauty of a given structure, or dynamic system (Alexander 1980). Some of these are (1) levels of scale, (2) strong centers, (3) boundaries, (4) alternating repetition, (5) local symmetries, (6) deep interlock, and (7) gradients. Alexander points out that these fundamental properties are not only found in man-made artifacts but are prominent in all natural structures and are thus also relevant to the structures studied by biologists. Indeed, in our experience, significant examples of all properties listed above are found in cells and organisms. Moreover, these properties are not only present as side products of biology; they are critical for the function of the structures and the processes in which they occur.

Alexander did not envision his architectural aesthetics being applied to biological systems. A further aesthetic element must be added to adapt his rich theories to create an aesthetics grounded in the phenomena of biological systems. This aesthetic element we believe is found in Alejandro Garcia-Rivera's notion of dynamic form. In order to directly test this idea, we propose to combine the empirical aesthetics of Alexander with Garcia-Rivera's notion of dynamic form and to apply this combined aesthetics to specific biological questions faced by modern biologists.

KNOWLEDGE IN BEAUTY AND NATURE

It is at this point where theology is poised to be helpful to the scientist who wishes to understand natural beauty. Although we do not claim that a scientist has to believe in a Judaeo-Christian God to find theological insights useful, we do claim that theological reflection has insights into the nature of ultimate reality from which science can profit. That Beauty is empirical has strong theological conviction. The church fathers recognized the observable objectivity of natural beauty and referred to it in their theological reflections. They saw this observable beauty referred to in Wisdom 11:20 ("But you have arranged all things by measure and number and weight," NRSV). Medieval Scholasticism took this Patristic love of natural beauty and began to articulate an aesthetics. Thomas Aquinas in his *Summa Theologia* articulates a necessary condition for beauty: "*pulchrum est quod visum placet*" (the beautiful is that when seen pleases) (*ST* I, q.39). This definition suggests an empirical aesthetics. Beauty is known when experienced through the senses. It is not simply known as an idea. Aquinas's empiricism is best articulated by the Spanish poet Antonio Machado (1983): "*El ojo que ves no es ojo porque tu lo veas, es ojo porque te ve*" (The eye you see is not an eye because you see it; it is an eye because it sees you). In other words, Beauty has an objectivity without which it would not be beautiful.

It is not surprising, then, that the claim of an empirical aesthetics may seem outrageous to those invested in an aesthetics seen purely in subjective or mental terms. Natural beauty, they would claim, has more to do with the observer than with the observed. We recognize a half truth in this claim. We do not deny that the beautiful has a subjective basis. Aquinas's definition gives us only the necessary, not the sufficient, conditions for the experience of beauty. Beauty's objectivity must engage our subjectivity and move us as well. For this reason, an empirical aesthetics must take into account both the objectivity and subjectivity of beauty (Garcia-Rivera 2008). This means we need an aesthetics different from those derived from the Grand Narrative. Indeed, we propose that a new set of aesthetic categories is needed to overcome a too-strict distinction between the subjectivity and objectivity of experience.

Garcia-Rivera (2007) suggests that dynamic form rather than efficient cause is the heart of natural reality. By dynamic form Garcia-Rivera means form characterized by the inextricable intertwining of structure and process that has a temporal dimension, that is, a beginning, a middle, and an end. By looking for an aesthetics of dynamic form, an empirical aesthetics is made possible. This has many implications for philosophy, biology, systems science, and theology.

The search for a new set of aesthetic categories is at the same time a search for new theological categories or, rather, the restoration of ancient theological categories now forgotten or hidden by the cloaking effect of our contemporary worldview. This search begins with the proposal that God's immanence is to be found in the natural beauty created by God's ordaining power. God's immanent ordaining power, in turn, has a strong trinitarian orientation that is best captured by church father Irenaeus's reference to God's ordaining activity. Irenaeus saw God's immanence in the world as the work of God the Father's two hands, namely, the Holy Spirit and the Logos (*Adversus Haereses, IV*, 28). Because the Spirit is the "Lord and Giver of Life" and the Logos is He "through whom all things were made" (Nicene Creed), two categories suggest a theological aesthetics, life and form.

Life as a theological category speaks of the contingency of creation, and *form* of the intelligibility of creation. Life as an aesthetic category recognizes the dynamism of natural beauty in its entire contingency. Natural beauty comes about through the dynamism of natural processes, processes that nonetheless have a beginning, a middle, and an end. In other words, living processes have a dramatic structure. The aesthetic category life brings into an empirical aesthetics is a dramatics. Life denotes the dramatic beauty inherent in nature's dynamism.

Form as an aesthetic category is more conventional. To introduce form into an empirical aesthetics of living systems, however, is also to introduce a new question to ask of empirical data. Form addresses the *whatness* of biological systems. Can the biologist meaningfully ask "What is a zebrafish?" Biology has avoided questions such as these by limiting its epistemology to analysis of process. Such an epistemology, however, lends itself only to knowledge of the parts of a system. To ask "What is a zebrafish?" is to ask "What makes the zebrafish be that which it is?" This is the question that Aristotle's substantial form attempts to answer.[5]

Substantial form speaks of a type of causality different from the efficient causality characterized in the analysis of process. To ask "What makes a thing be that which it is?" recognizes a causality that is different from the ones that make machines run. It is the causality that explains the activity of the whole as a whole. It is the principle by which the many possibilities of molecules and cell parts and cells become this particular living whole. Formal causality is not a causality that forces an effect but the unifying principle that brings the many possibilities of parts into a living whole. It is causality from the inside out as opposed to the bottom-up (Dodds 2000).

A theological aesthetics of creation that would account for the role of the Holy Spirit in creation, however, suggests that form or formal causality in the Aristotelian sense is not enough. Much better is to rethink substantial form in terms of the category of life. Doing so transforms substantial form into what we call dynamic or living form. As such, dynamic form can serve to represent the immanent reality of Nature. This immanent reality can be traced ultimately to God's divine ordaining power as realized through God's two "hands": the Logos and the Holy Spirit. Both Logos and Holy Spirit give intelligibility and contingency to the universe. Through this intelligibility and contingency, the universe, the Father wills more than a unity of forms. The universe becomes a cosmos of "endless forms most beautiful" willed by the trinitarian power of the Creator.[6]

Thus, dynamic or living form emerges as an aesthetic category that goes beyond the meanings of form received from the Greek philosophical tradition. Living form has an empirical base and somehow combines two philosophical categories meant to be opposites: form and flux. Dynamic form inextricably combines structure and process. As such, it goes to the heart of the root intelligibility of the discipline of biology itself.

By applying these modified principles of empirical aesthetics to specific problems of experimental design in cell and developmental biology, on the one hand, and to the modeling of complex cellular systems by computer simulation, on the other, we propose to show that empirical aesthetics can greatly improve both experimental design and model building in the life sciences.

DYNAMIC FORMS AND BIOLOGICAL SYSTEMS

Traditionally, *form* describes the unchanging aspect of what exists that is otherwise in flux. In that sense, the term *dynamic form* is an oxymoron. However, some relationships change much more slowly than others providing the illusion of permanence. With discovery of the Big Bang and the eventual creation of the elements scientists know that nothing natural has existed forever, which means that all that exists now had to come into existence, and that involves change. One could discard *form* as antiquated, but then one would need to develop a new construct to describe the relatively stable aspect of what changes more rapidly, and without the benefit of two millennia of scholarship. Thus, *dynamic form* captures the permanent aspects of phenomena under investigation while acknowledging their eventual change.

Scientifically, dynamic form hides the slowly changing aspects, which the scientist chooses to ignore, such as the 14 billion–year changes in cosmology and the 4 billion–year changes in geology while studying the earth's current geography, or the 14 billion–year changes in cosmology and the 2 billion–year changes in evolution while studying the changes in mental function in humans over the past one hundred years. In particular, biology postevolution requires dynamic form where one can study the form of an organism as it developed over an individual lifespan and ignore the slower, dynamic shift of species as they evolve. Encapsulation from object-oriented analysis suggests a method for hiding the slower-changing (evolving) relationships and the relationships that occur on a smaller scale.

Philosophers in late antiquity assumed form to be static, that is, active but not evolving, and prior to physical existence. Although significant in early "scientific" accounts of nature, modern scientific discussion excludes form and relegates it to artistic endeavors. However the a priori, essentialist and reductionist philosophical approaches assumed in the early development of modern science have proven inadequate to explain the more recent advances of evolution, cosmology, and quantum mechanics (for example, Ellis 2005).

Although the ancient philosophical category of form categorizes the relationships and emergence examined by molecular and systems biologists, and philosophers of science may describe the parallels, contemporary scientists typically do not use the category of form (other than perhaps by analogy to architecture and artistic endeavors). A significant limitation to scientists using the rich, philosophical construct of form to define systems more rigorously and use them more effectively results from the preevolution definition of form as *substance* or *essence*. By reconstituting the category of form as *dynamic form* to allow for the appearance of stability amid slower-changing relationships, scientists can draw upon a richer philosophy of nature to address pressing scientific issues for which otherwise they can draw only upon personal, idiosyncratic intuitions or mistaken nineteenth-century misconceptions of nature and other fields of science.

Scientist-theologian Arthur Peacocke (1993, 44–45) argues against taking a static view of the world because almost all entities and relationships are subject to change, though on widely disparate time scales. He believes that the world can be described in terms of the changes over time to entities and relationships, and science can reliably attribute causality only when "some underlying relationships of an intelligible kind, between the successive forms of the entities have been discovered" (p. 45). The explanatory relationships involve an understanding of both how the entity's constituent relationships give it the form it has and how changes in the internal relationships manifest themselves as observations on the system as whole.

Substantial form is a primitive philosophical category, and artists, architects, and aesthetic philosophers have described many characteristics of aesthetic form. Studying dynamic form requires knowledge of its internal structure. Systems theory provides a structure for dynamic form. For which relationships constituting a system does one ignore (encapsulate) the change? Peripheral relationships change and have no significant effect on an entity studied. Similar to Aristotle's accidental form, "accidental" relationships change the arrangement, appearance, or contour of the entity, but it retains continuity of identity. One ignores the other slowly shifting, evolving, but still dynamic relationships.

Scientists must now reexamine their philosophical presuppositions to develop adequate models of reality. If the world supported a reductionist and static worldview, an accurate philosophy of nature might require only Aristotle's substantial form and not forms that evolve dynamically. For Peacocke, the relationships of the natural world have a dynamic character. One cannot separate the observed structures of the world from how they came to be that way. History is a seamless web of continuity. For Peacocke, "the 'being' of the world is always also a 'becoming'" (pp. 61–62).[7]

FORM AS INFORMATION

Patterns of information flow (in terms of molecules with distinct properties) provide order and sufficient stability over time to determine the complex interactions that ensure biological life. Examples of information flow in biology include metabolic pathways, ion flow for neuron activation, and genetic signaling pathways. Peacocke suggests that form can describe patterns of information, which are stable. In emergent systems, self-organization engenders new patterns and forms of organization. Peacocke describes that aspect of emergence as a "determination of form through a *flow of information*" (p. 59). He conceives of causal effectiveness as the transfer of information rather than the transfer of energy (pp. 50–61). As the universe appears dynamic, emergent, and without a mechanistic ground, an accurate philosophy of nature requires a coherent model of emergent relationships. In the revised interpretation, form is described as the information content of emergent systems.

We explore here the role of beautiful, dynamic forms in nature, and in particular the role of form in modeling biological systems with the first aim of describing how dynamic forms capture the difference between the whole and the sum of the parts and the second aim of understanding the role beauty plays in dynamic forms. Systems scientist Gregory Bateson defines information as "differences that make a difference" (1979, 87), which correlates with Peacocke's interpretation of form as a flow of information. Although difficult to define precisely what, by definition, cannot be reduced, computer science predominately works within the virtual space of information, and systems theory makes the structural information of relationships precise. The role that beauty plays both in the modeling of dynamic form and in the human element of experience also engages a spiritual nexus between science and theology that is amenable to the methods of the rising field of theological aesthetics.

Relationships carry information. Bateson defined information as a difference that makes a difference, and the first information scientist, Claude Shannon, specified information as separate from energy or matter, because information can easily flow opposite to energy or be communicated by the lack of energy as occurs, for example, in switches. One can measure the amount of information conveyed by the number of yes/no (binary) decisions, called a *bit*, required to communicate a selection among the alternatives. In engineered systems or communication between systems with an interpretive component, those choices are predefined for Shannon's information. For example, to choose among eight items requires three yes/no decisions.[8]

In natural systems, the interpretations that define the choices emerge with the systems that carry them, and that requires the philosophical category of form. Form carries information about how the parts are arranged, appear, or have contour out of all possible alternate forms (Tatarkiewicz 1980, 220–43). Adding a drop of paint to a painting may change all other relationships within the painting in comparison to how other drops might have been added. Working within the space of possible forms opens up a mathematical and logical space in which one can identify forms in relation to alternatives. For any particular purpose, those relationships would carry information: Some drops of paint are significant to the form; others are indistinguishable or even noise.

From a theological perspective, the beauty of the relationships between possible and actual natural forms captures our interest with the hope that understanding how the book of Nature is illustrated may communicate something of its Author-Artist. From a scientific perspective, one may explore that space of possible forms to engineer applications that effectively and efficiently represent and communicate actual forms for computer vision, artificial intelligence, compression algorithms, systems biology, and so on. From a theology-and-science perspective, examining beauty in the forms of nature requires a precise formalism for characterizing forms and their relationships.

MODELING FORM AS SYSTEMS

Computer science often typically captures the form in computational models, or programs and data structures, that represent the structure and function of the engineered, natural, or occasionally social forms under examination with the purpose of simulating or querying the computational model to make predictive or unrealized discoveries of the corresponding natural phenomena. However, rather than use the language of form, computer scientists often talk about systems.

Systems theory analyzes relationships of phenomena in the context of the systems that those relationships constitute. Significant for this essay are natural systems within biology as well as computational models of those systems that define virtual systems. A *system* consists of a configuration of relationships that maintain that configuration as stable with respect to changing environmental influences. It is a relationship of relationships stable enough to become part of additional relationships. Systems maintain stability by allowing some of their relationships to change and holding others constant (as needed in a more dynamic understanding of form).

One framework for modeling systems on a computer is object-oriented analysis and design. In object-oriented analysis, one models each natural or engineered entity as an object, and in the design phase one uses programming language structures to create a computational model of what was analyzed. An *object* consists of a collection of attributes or relations between entities (its structure) and methods that the entity can perform (its function). In programming languages, objects also have *encapsulation*, which ensures that attributes are changed only through the programs coupled to the object, called "methods," and not directly by another object. An *attribute* may have as a value either an atomic (primitive and undefined) value or another object. Objects with identical structure and function (though possibly different values) define a type, typically called a *class*.[9]

Object-oriented analysis uses a systems approach to create a representation of a natural or engineered entity that one can model on a computer. Although objects are insufficient to model human systems, they easily capture simpler aspects of systems, and two concepts from object-oriented analysis and design are important for the computational definition of dynamic form: the concept of class—a collection of objects with identical structure and function but possibly different values—and encapsulation, which hides some information and creates an *interface* (or boundary) by which other objects interact with the defined object. In computer programming with objects, called object-oriented programming, hidden aspects are protected from change by other objects increasing system stability and facilitating long-term management and change of the system.

Using objects to model biological systems is not new, and those computational approaches had some success, but they also suffered from the static and unchanging definition of object classes, which does not capture the dynamic relationships of biology (Graves, Bergeman, and Lawrence 1995). Computational models for biology require a different modeling mechanism that allows not only the value of objects to change over time (their accidental form) but also the structure of classes (their substantial form), and that requires more philosophical sophistication than typically goes into development of computational systems.

How can one model the information content of the form of a system not already captured by the information content of its constituent parts?

For a formalism to describe the information content of possible and actual forms, we draw upon Alexander's work with "centers" as a basis for logical representation. Because forms occur in a space of possibility, the logic does not define the forms' actual relationships but constraints on what those relationships might become, and the philosophy and logical categories of Charles Peirce make that distinction precise. We compare the adaptation of Alexander's *Pattern Language* (Alexander, Ishikawa, and Silverstein 1977) by computer scientists beginning in the 1990s to software design patterns (Gamma 1995) by adapting his empirical aesthetics as outlined in *The Nature of Order* (2002a) to the computational modeling of natural systems, specifically in molecular and developmental biology.

Alexander explains wholeness in terms of centers. The components of a system exist chiefly in relation to the whole. Instead of wholeness resulting from a relationship among parts, the whole defines the parts. The parts, or "sub-wholes," are also centers, and thus relationships between centers define other centers. Centers result from the wholeness and undergo modification by their position within the whole. Rather than considering a flower as composed of petals, the petals are identified by their role and position in the flower. Antithetical to Cartesian or mechanistic thinking, Alexander's approach evokes the discussion of "fields" in physics rather than "objects" and resonates with similar insights into biological systems (Alexander 2002b, 80, 86–88). Alexander's use of centers suggests a way to focus not just on the whole or the parts but also on the relationship between the two. Focusing on the relationship between wholes and parts and reconciling the holist and reductionist interpretations of systems require cultivating an aesthetic sensibility and, for fruitful scientific models, require exploring the beauty in nature.

A center refers to the nexus of relationships that form a whole apart from the boundaries that "a whole" implies (p. 85). For Alexander, the center of an entity exists before the parts (p. 86). The entity that will become "a part" may exist independently, but becoming a part depends on a relationship between its center and the center of what will become the whole. Although not stated explicitly by Alexander, logically the center of the whole must exist prior to the part relationship, and to explore the logical relationships between the centers that do and do not yet exist requires a modal logic.

A further explanation of a logical basis for Alexander's centers is outside the scope of this essay. Instead, we demonstrate how Alexander's centers can model relationships in systems biology.

SYSTEMS BIOLOGY

We propose that the application of aesthetic principles as a scientific tool may be especially relevant for systems biology. This relatively new field seeks to characterize living systems in their totality by defining the global properties of the system that emerge out of the dynamic relations of its constituent parts. This difference in perspective has important consequences for methodology. Whereas classical molecular biology attempts to model relatively small parts of a living system based on available experimental data (obtained by examining the parts in isolation), systems biology aims to generate a simulation of an entire system even in the absence of all required experimental data. This is because "we are unlikely to ever know the exact characteristics of all cellular components with high precision" (Karsenti, Nedelec, and Surrey 2006, 1205).

How can one model a whole living system without knowing all of its details? We suggest that a strong sense of aesthetics is critical for this approach, to guide the process of filling in blank areas of a model with hypothetical interactions. These can then be tried out by computer simulation and followed by experimental validation.

Lack of awareness of form limits the development of complex models of the relationships in molecular biology. The usefulness of a systems approach in general biology is well documented, and the rapid increase in complexity of knowledge in molecular biology post–Human Genome Project (June 2000) has initiated a substantial increase in systems approaches to molecular biology.[10] Although only a few researchers focused on "systems biology" in the mid-1990s because of a lack of generally available data and computational tools, in the past decade dozens of major centers, institutes, and organizations have been created as well as major initiatives at most major medical centers and pharmaceutical companies, including the first new department at Harvard University in twenty years (Check 2003).

It is well known that many properties of natural systems can be described in terms of mathematical equations. If this is the case, and if the criteria of elegance and beauty are useful for finding the best mathematical equations, those same criteria must also be useful for understanding biological systems in general. One of the best known mathematical models for biological pattern formation is the "Reaction-Diffusion" (RD) model, based on a seminal paper by Alan Turing ([1952] 1992), in which he showed mathematically that small random fluctuations in a system composed of two reacting and diffusing chemicals can be amplified and that this process can lead to the generation of spatial pattern in such a system.

The essential feature of a reaction-diffusion system is the presence of two or more distinct types of molecules that are diffusible and that interact with each other. In the simplest example, the system contains an activator molecule that stimulates both its own synthesis and the synthesis of an inhibitor molecule, which in turn inhibits synthesis of the activator. If, in addition, the inhibitor diffuses more rapidly than the activator, a closed system with initially uniform distribution of both molecules can spontaneously develop a wavelike pattern with a peak of activator. If the size of the system is increased, two peaks will develop, and so on, leading to the generation of a periodic pattern. This mechanism also can be used to generate a periodic pattern in two or three dimensions. Turing argued that such a molecular prepattern can be used by developing organisms as a template guiding the formation of biological structures, and he coined the term *morphogen* to describe the molecules that form these prepatterns.

The work of Turing inspired a great deal of mathematical research and has been used to propose models for the molecular mechanisms giving rise to pattern elements throughout the animal kingdom, ranging from zebra stripes to the coloration patterns on sea shells (Meinhardt, Prusinkiewicz, and Fowler 1995). These models are attractive because of their relative simplicity and because they are sufficient to explain how spatial pattern self-organizes in a closed system once the system has been set up in the appropriate way. In addition, reaction-diffusion mechanisms can explain how new pattern elements are added in a growing system, with the correct temporal and spatial sequence. And because growth is a property of the vast majority of biological systems, it must be taken into consideration by any model seeking to describe pattern formation in developing organisms.

In spite of the elegance and explanatory power of the reaction-diffusion model, it has been the subject of great controversy among biologists and has been rejected by many as being too simplistic (Akam 1989). Hence it is important to stress that until recently the reaction-diffusion model was a proposal for how biological systems *could* be organized, not the way they *are* organized. Indeed, many biologists have argued that the model is not helpful because it is not based on empirical data.

Despite this opposition, biologists have continued to test the reaction-diffusion model, and in 2006 a major breakthrough occurred when the first compelling evidence was presented to support the use of a reaction-diffusion mechanism to regulate hair follicle spacing in mouse skin (Sick et al. 2006). The proteins WNT and DKK are secreted morphogens that diffuse through the extracellular space of mouse skin, and WNT functions as an activator that triggers hair follicle formation. WNT also triggers expression of DKK, which in turn functions as an inhibitor by binding to WNT protein and blocking its activity. Given that WNT protein is substantially larger than DKK, it is expected that DKK diffuses more rapidly than WNT in the extracellular space. This combination of a short-range activator with a long-range inhibitor is astonishingly similar to the simplest form of the Turing reaction-diffusion system described above.

A systems analysis of these relationships can be graphed as shown in Figures a and b, split into two diagrams for readability. Each labeled vertex in the graph (ellipse) refers to a center in the analysis of the WNK-DKK reaction-diffusion, and each edge refers to a relationship between centers. For example, DKK inhibits WNT, and DKK binds to WNT. The rectangular vertices refer to emergent properties of centers, such as diffusion rates, that have meaning for the center only when considered as a whole.

Once a systems analyst has developed these diagrams, software developers can turn them into data structures to store or process scientific data,

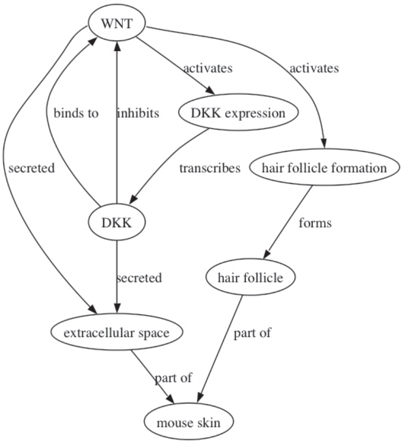

Figure a

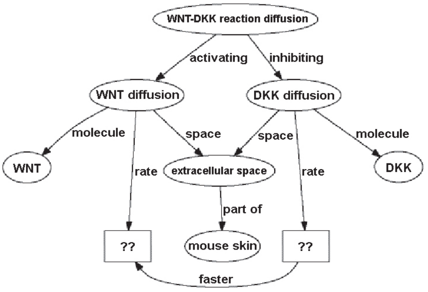

Figure b

but comprehensive, consistent, compact, fruitful, and robust models require that the virtual forms of the systems modeled computationally correspond with the natural forms discovered by scientists.

S. Sick and colleagues tested their model by experimentally manipulating the level of DKK inhibitor protein. Computational modeling predicts that moderate overexpression of the inhibitor should lead to increased spacing between hair follicles whereas strong overexpression should abolish hair follicle formation completely. These are exactly the results observed by the authors upon moderate, or strong, overexpression of DKK protein in the mouse skin, providing compelling evidence for a reaction-diffusion mechanism as a key determinant of hair follicle spacing in this organism.

The reaction-diffusion model is thus an excellent example of a scientific breakthrough that started as a beautiful idea—in this case an elegant mathematical model for pattern formation in biology. Strikingly, it took more than fifty years before the model was supported by empirical evidence and confirmed by experimental testing in a specific biological context. During these fifty years the model attracted a lot of attention, not because of the empirical evidence supporting its validity but because of its beauty. Lesser models would not have survived so long in the absence of supporting evidence, and indeed there have been plenty of attempts to reject the reaction-diffusion model as a theoretical flight of fancy. Now, in light of the experimental demonstration by Sick and colleagues, the Turing model is no longer just a beautiful proposal for the way that spatial patterning in biological organisms *could* be organized but an accurate description of the way spatial pattern in a particular organism *is* organized.

The validation of Turing's elegant reaction-diffusion model shows how beauty can be a guide toward truth in science. This is possible only if beauty is an objective property of natural systems, and thus confirms our view that the recognition of beauty is of practical use for guiding experiments and model building in science.

CONCLUSIONS

The theology-and-science dialogue often has taken the form of theology accommodating to the theories science has of natural reality. Rarely has theology been an equal partner with science in the understanding of natural reality. We believe that theology's long tradition of reflecting on natural beauty has been a neglected resource in the dialogue. It has been neglected as a resource for understanding natural reality because of the shift that occurred in our understanding of beauty with the birth of science as well as our understanding about the nature of the experience of beauty, that is, the beautiful.

We propose that "beauty is in the eye of the beholder" is a half-truth when it comes to natural beauty. We have given empirical evidence that points to the other half of beauty's truth: It is a fundamental property of natural reality. This proposal has important implications for both theology and science. For theology, it means rediscovering an ancient tradition that opens up new avenues of theological reflection: the tradition of divine action in the world, the *potentia Dei ordinata*—the ordaining power of God. When this aspect of God's power is coupled to formulation of God's immanence in creation, the beautiful forms of natural reality become real signs of God's divine action. Beautiful forms may not be the "fingers" of God in creation, but they certainly can be seen as the "fingerprints" of God. More important, a vigorous connection of God's action with the reality of nature opens up the possibility of a theological cosmology. By theological cosmology we mean less a theology of nature than an account of God's intimate connection to the structures and processes of natural reality, an account we believe cannot be ignored if theology is to be truly systematic.

That natural beauty is a sacred manifestation of God's immanent power in nature ought to give theologians, philosophers, and spiritually oriented scientists pause, for in this insight theology becomes, hopefully, a welcomed partner in the discovery of the principles and processes that govern natural reality. The discovery that beauty is a fundamental property of natural reality may also change our scientific way of the world. Natural reality viewed only from the perspective of the parts will then be complemented by a perspective of the whole. Moreover, these two will find their true connectedness in an empirical aesthetics that discovers the relationships between the two.

As such, an empirical aesthetics promises to reenchant a reality too long made stark and barren by reductionist approaches. Moreover, if natural beauty is found to be a fundamental property of nature, the possibility exists for the development of an ethics that can help science make wise choices in the enterprise of scientific progress as well as provide a basis for justifying the continuing inquiry into the processes and structures of natural reality.

Natural beauty as a property of ultimate reality also may provide new lines of philosophical inquiry in both the philosophy of art and metaphysics. As such, philosophy may once again become part of the scientific process instead of a marginalized reflection on science's achievements. Although we presented only one example to demonstrate our claim, many others could have been chosen. We hope that theological reflections on the beauty in biological systems can become the beginning of a new and fruitful conversation between science, theology, and philosophy rather than an end.

NOTES

1. For a history of how these two views of God's power have influenced theological understandings of Nature see Funkenstein 1986. For the theological implications see the discussion in Garcia-Rivera 1999.

2. For a good overview of the field, see Hull and Ruse 2007.

3. To understand the significance of aesthetics in science, it is important to ask scientists about their experience of the role of beauty in science. In preliminary conversations we conducted with scientists, the view emerged that an attraction to aesthetics plays a role not only in interpretation of experimental findings but also in experimental design. One scientist felt that beauty is connected to the unknown aspects of a system of interest and that a sense of aesthetics helps to intuitively select the most plausible interactions underlying an unknown phenomenon, which can then be tested experimentally. Interestingly, C. J. Neumann (2007) explored creativity in science where many scientists identified intuition as important for guiding their creative breakthroughs. In light of this new statement, intuition might be defined as the unconscious application of aesthetic principles to a given set of observations to connect them in the best way, thereby giving rise to a model free from internal contradiction. In that case, making these aesthetic principles available as a conscious tool would be highly beneficial for scientists. It would acknowledge the value of a well-developed sense of aesthetics for doing science and could even lead to the inclusion of aesthetic training as a part of science education.

4. This is not a new proposal. Alfred Tauber explored the role of beauty in science in a series of essays he called the Elusive Synthesis. Unfortunately, the essays concentrate more on art theory than aesthetics per se. Nonetheless, many fine insights can be found in Tauber 1996.

5. For a good overview of the philosophy of form and formal causality see Wallace 1996.

6. A more detailed discussion of dynamic form is found in Garcia-Rivera 2007.

7. Although Peacocke's "becoming" is temporal rather than metaphysical, it provides a metaphor for metaphysical investigation.

8. The log base 2 of the eight possible decisions. Split the eight items into two groups of four. First decision: Choose between two groups of four. Split the chosen group in half. Second decision: Choose between two groups of two. Split the chosen group into its individuals. Third decision: Choose between the two individuals.

9. Objects also have *inheritance*, where attributes and methods are shared, but inheritance is not relevant for the current study. Technically, the given definition of an object without inheritance actually defines an abstract data type. In terms of linguistic type-token distinction, a class is the type and objects are the tokens.

10. A note on terminology: Older fields of biology have drawn heavily upon systems theory to model complex relationships and synthetic or "emergent" approaches (considering the whole as greater than the sum of its parts) since the 1970s. These fields include integrative biology, ecology, and so on. More recently, the fields of molecular biology, molecular genetics, genomics, proteomics, bioinformatics, and so forth have attended to the area of biological interactions among complex molecules and their models in the field called systems biology. Although difficult to distinguish among these new, rapidly developing fields—even for some of the scientists involved—the methods used typically differentiate between molecular biology experiments (performed in a "wet" lab) and systems biology models (which require computational support for representation, modeling, or simulation). By addressing systems and molecular biology, we focus on the most recent, complex experiments that require collaborative effort by scientists with expertise in molecular biology and computer science who develop large, high-throughput experiments to investigate numerous biological interactions in parallel in a manner amenable to effective exploration of those relationships.

REFERENCES

Akam, M. 1989. "Drosophila development: Making stripes inelegantly." *Nature* 341 (6240): 282–83.

Alexander, Christopher. 1979. *The Timeless Way of Building*. New York: Oxford Univ. Press.

———. 2002a. *The Nature of Order: An Essay on the Art of Building and the Nature of the Universe.* Berkeley, Calif.: Center for Environmental Structure.

———. 2002b. *The Phenomenon of Life: An Essay on the Art of Building and the Nature of the Universe*. Berkeley, Calif.: Center for Environmental Structure.

———. 2007. “From Small-Scale Human Minutiae as Important in Architecture, to a Changed View of the Universe 2007.” *http://www.natureoforder.com/library/minutiae-to-universe.htm.*

Alexander, Christopher, Sara Ishikawa, and Murray Silverstein. 1977. *A Pattern Language: Towns, Buildings, Construction*. New York: Oxford Univ. Press.

Bateson, Gregory. 1979. *Mind and Nature: A Necessary Unity*. New York: Dutton.

Check, E. 2003. “Harvard heralds fresh take on systems biology.” *Nature* 425 (6957): 439.

Dodds, Michael. 2000. “Top Down, Bottom Up or Inside Out? Retrieving Aristotelian Causality in Contemporary Science.” In *Science, Philosophy and Theology: The Notre Dame Symposium 1997*, ed. J. P. O’Callaghan. New York: Saint Augustine’s Press.

Ellis, George. 2005. “Physics and the Real World.” *Physics Today* 58 (7): 49–54.

Funkenstein, Amos. 1986. *Theology and the Scientific Imagination from the Middle Ages to the Seventeenth Century*. Princeton, N.J.: Princeton Univ. Press.

Gamma, Erich. 1995. *Design Patterns: Elements of Reusable Object-oriented Software*. Addison-Wesley professional computing series. Reading, Mass.: Addison-Wesley.

Garcia-Rivera, Alejandro. 2007. “Endless Forms Most Beautiful.” *Theology and Science* 5 (2): 125–35.

———. 2008. “On a New List of Aesthetic Categories.” In *Theological Aesthetics after Hans Urs Von Balthasar*, ed. O. Byrchov, 169–86. Oxford: Ashgate.

Garcia-Rivera, Alex. 1999. *The Community of the Beautiful: A Theological Aesthetics*. Collegeville, Minn.: Liturgical Press.

Graves, Mark, Ellen R. Bergeman, and Charles B. Lawrence. 1995. “Graph Database Systems for Genomics.” *IEEE Engineering in Medicine and Biology* 11 (6): 1–18.

Hull, David L., and Michael Ruse. 2007. *The Cambridge Companion to the Philosophy of Biology.* Cambridge and New York: Cambridge Univ. Press.

Karsenti, E., F. Nedelec, and T. Surrey. 2006. “Modelling microtubule patterns.” *Nature Cell Biology* 8:1204–11.

Machado, Antonio. 1983. “Proverbios Y Cantares.” In *Times Alone: Selected Poems of Antonio Machado*, ed. R. Bly, 142–43. Middletown, Conn.: Wesleyan Univ. Press.

Meinhardt, Hans, Przemyslaw Prusinkiewicz, and Deborah R. Fowler. 1995. *The Algorithmic Beauty of Sea Shells, The Virtual Laboratory*. Berlin and New York: Springer-Verlag.

Monod, Jacques. 1972. *Chance and Necessity: An Essay on the Natural Philosophy of Modern Biology.* New York: Vintage Books.

Nagel, Ernest. 1979. *The Structure of Science: Problems in the Logic of Scientific Explanation*. 2d ed. Indianapolis: Hackett.

Neumann, C. J. 2007. “Fostering Creativity. A Model for Developing a Culture of Collective Creativity in Science.” *European Molecular Biology Organization Report* 8 (3): 202–6.

Peacocke, Arthur Robert. 1993. *Theology for a Scientific Age: Being and Becoming—Natural, Divine, and Human*. Enlarged ed. Minneapolis: Fortress.

Robert, Jason Scott. 2007. “Molecular and Systems Biology and Bioethics.” In *The Cambridge Companion to the Philosophy of Biology*, ed. David L. Hull and Michael Ruse, 361–71. Cambridge and New York: Cambridge Univ. Press.

Russell, Bertrand. 1918. *Mysticism and Logic, and Other Essays*. New York: Longmans, Green.

Sick, S., S. Reinker, J. Timmer, and T. Schlake. 2006. “WNT and DKK determine hair follicle spacing through a reaction-diffusion mechanism.” *Science* 314 (5804): 1447–50.

Tatarkiewicz, Wladyslaw. 1980. *A History of Six Ideas: An Essay in Aesthetics*. Hingham, Mass.: Kluwer Boston.

Tauber, Alfred I. 1996. *The Elusive Synthesis: Aesthetics and Science*. Boston Studies in the Philosophy of Science 182. Dordrecht and Boston: Kluwer.

Thoreau, Henry David. 1906. *The Journals of Henry D. Thoreau.* Boston: Houghton-Mifflin.

Turing, Alan M. [1952] 1992. “On the Chemical Basis of Morphogenesis.” *Philosophical Transactions of the Royal Society of London*, Series B, 237, 37–72.

Wallace, William A. 1996. *The Modeling of Nature: Philosophy of Science and Philosophy of Nature in Synthesis*. Washington, D.C.: Catholic Univ. of America Press.