AN INQUIRY INTO THE ORIGINS OF LIFE ON EARTH—A SYNTHESIS OF PROCESS THOUGHT IN SCIENCE AND THEOLOGY

by Ross L. Stein

Abstract. An initiating event in the development of life on earth is thought to have been the generation of self-replicating catalytic molecules (SRCMs). Despite decades of work to reveal how SRCMs could have formed, a chemically detailed hypothesis remains elusive. I maintain that this is due, in part, to a failure of metaphysics and question this research program's ontologic foundation of materialism. In this essay I suggest another worldview that may provide more adequate ontologic underpinnings: Whitehead's process philosophy of dynamic, relational becoming. Here we come to see molecules not as unchanging objects but rather as processes that possess the capacity for subjective experience. Molecular transformation is driven by experience, both internal and external. Process thought accounts for the world's creative impulse by positing a God who lures the becoming of all entities toward greater complexity and value. Chemical evolution is now seen as divine motivation of molecular becoming and, as such, possesses the potential for introducing true novelty into the world. The "causal joint" between God and world is hypothesized to be an energy transduction at the molecular level that allows divine action without violation of chemical principles or physical laws.

Keywords: abiogenesis; origins; process philosophy; Alfred North Whitehead.

Abiogenic research is an active area of scientific inquiry that seeks to construct naturalistic hypotheses for the origins of life based on findings from multiple disciplines, including chemistry, geology, and chaos/complexity

Ross Stein is Associate Professor of Neurology at Harvard Medical School and Director of the Laboratory for Drug Discovery in Neurodegeneration of the Harvard Center for Neurodegeneration and Repair, 65 Landsdowne Street, Cambridge, MA 02139; e-mail rstein@rics.bwh.harvard.edu.

[*Zygon*, vol. 41, no. 4 (December 2006).]
 ISSN 0591-2385

theory. One of the goals of this research is to draw a chemical mechanistic line from primal, inorganic matter of the early Earth to the first self-replicating catalytic molecule (SRCM), and from this to the first autonomous cell-like structure. In this essay I focus attention exclusively on SRCMs and explore how these highly specialized molecules might have arisen.

Questions of origins are among the many Ultimate Questions that humans have always asked. Ultimate Questions are those that probe and tease apart the existentially urgent aspects of our lives. During the many centuries in which we have sought answers for these questions, we have developed three fundamental modes of inquiry, three ways of framing and approaching our concerns: theology, philosophy, and science. Although some of our questions can be addressed through studies that principally rely on just one of these modes of inquiry, other questions require concerted application of two or all three modes.

When trying to understand how life originated, we generally have relied on either theology or science, with little progress being made. Theology when done in isolation from contemporary science provides mythopoeic accounts that lack factual accuracy. Scientific investigations into the origins of life, while making some progress, have yet to yield a truly workable hypothesis. My goal here is to explore the abiogenesis question as a problem in "scientific metaphysics" (Lee 1947; Bunge 1971; Lange 2002) and provide a new ontologic framework that will allow the construction of a comprehensive abiogenic hypothesis. From a stance grounded in Alfred North Whitehead's philosophy of organism, or process philosophy, I draw on the resources of theology, philosophy, and science and try to formulate a hypothesis that describes what a world must be like for life to arise in it.

OUTLINE OF ESSAY

In the first section, *Current Status of Abiogenic Research*, we see that despite the absence of a coherent, chemically informed abiogenic hypothesis there is a well-founded consensus that very early in the development of life on Earth SRCMs must have arisen. More specifically, these SRCMs were likely peptides (that is, self-replicating catalytic peptides, or SRCPs) and would have had the ability to not only catalyze their own formation but also the many other reactions that made up the chemical choreography of the first rudimentary metabolic pathways.

Next, in *Generation of Self-Replicating Catalytic Peptides*, I describe how SRCPs may have formed. Although this section is necessarily highly schematic in nature, it is based on sound principles of chemical mechanism and dynamics. The section ends with an assessment of the likelihood of SRCP formation, which by any reckoning is quite low. For the sake of argument, I assume an extreme position and maintain that this probability is precisely zero, *if* the world we inhabit is the materialistic world of modern science, of unchanging, nonexperiencing substance. Of course, this begs the question: If not the materialistic world of modernity, what then must our world be like for the first SRCP to have arisen in it?

In the next section, *A Process Universe—Panentheism, Panexperientialism, and Self-Replicating Catalytic Peptides*, with Whitehead's process philosophy as my touchstone, I develop an answer to this question. I review those aspects of Whitehead's philosophy that directly apply to this project. Whitehead gave us a remarkable picture of reality in which the actual entities of this world are not vacuous, nonexperiencing substance but rather nodes of concentrated energy that enjoy subjective experience. His philosophy gives ontologic priority to becoming over being, where the becoming of every actual entity is a process that draws into experiential relation all other entities, including God, who lures all entities toward greater complexity, beauty, and novelty. We will see that this is a panentheistic God, a "living person" (Griffin 2001, 156–63) who both experiences and is experienced by the world.

In the final section, *Chemical Evolution as Divine Motivation of Molecular Becoming*, I build on Whitehead's thought and construct an explanatory hypothesis for the "causal joint" between Creator and creation and how God is able to flex this joint. I first establish the concept that the emergence of catalytic capabilities in particular molecules was a critical result of an general evolution of chemical potentials, which was itself a synthesis of two types of teleologic activity—actualization of inherent *potential* and influence by *goals*. The latter reflects Whitehead's concept of the "initial aim" of God that is experienced by all of the world's entities toward greater complexity and value. Deeper insight into how God acts in the molecular world comes when we take seriously Whitehead's notion that God is as an actual entity and, like all actual entities, is both energy and a transducer of energy. Combined with principles from a process philosophy of chemistry (Stein 2004; 2006), we are led to the proposition that God is able to alter the energy distribution within a system of reacting molecules in such a way as to favor a specific set of reaction products over another. This allows realization of a "molecular teleology" without violation of chemical principles or thermodynamic laws.

Current Status of Abiogenic Research

The modern era of abiogenic research can be said to have begun with the now famous experiments of Stanley L. Miller and Harold Urey in the early 1950s (Miller 1953; 1955; Miller and Urey 1959). These studies established that amino acids and other organic chemical precursors of the macromolecules required for life can form from simple inorganic materials under conditions that might have existed on our planet after it cooled some four billion years ago. These experiments laid the foundation for the research activities of generations of prebiotic chemists and other origins-of-life scientists in the decades since (for reviews see Sutherland and Whitfield 1997; Orgel 1998; Maurel and Decout 1999; Rode 1999).

But, as Michael Denton reminds us, "despite enormous efforts, we still have no idea how this [origin of life] occurred, and the event remains as enigmatic as ever" (1998, 293). With similar sentiments, Noam Lahav and his colleagues at Hebrew University of Jerusalem begin a recent review on the chemical basis for the emergence of life with these words: "After almost 50 years of modern research, there is no paradigm of the origin of life" (Lahav, Nir, and Elitzur 2001). Hypotheses about an early RNA-world are chemically untenable and have yet to offer solutions to the myriad problems that the inherent instability of RNA creates (Orgel 1998). A primal iron-sulfur world of life-generating deep ocean vents has also been proposed. While this hypothesis has the air of plausibility due to the existence of hardy bacteria that can thrive in such harsh environments, it has been unable to advance beyond the catalysis of simple chemistries (Martin and Russel 2002). On the theoretical front, thinkers such as Stuart Kauffman have provided extraordinarily detailed computer-generated accounts of the self-assembly of autocatalytic molecules (Kauffman 1993, 287–341). These simulations are indeed fascinating and may serve as useful exercises in model building, but they lack chemical realism and are inadequate guides for what might have occurred. Faced with such bleak prospects for ever understanding abiogenesis Francis Crick admitted that "the origin of life appears at the moment to be almost a miracle, so many are the conditions which would have to be satisfied to get it going" (1981, 88). Motivated by this appraisal, Crick proposed the idea of Directional Panspermia in which life originated not on Earth but rather from bacteria that were seeded here by an advanced alien civilization. It seems that Crick and other biologists have come to realize that the spontaneous development of the first single-celled organism in the radically hostile environment that the earth offered three and half billion years ago is extraordinarily improbable (Ward and Brownlee 2000).

Of course, this may be too harsh and skeptical an assessment of the current status of abiogenic research. While this work may not be proceeding at the pace we would like, we must realize that the problem being addressed is enormous. And, in fact, some progress has been made. Abiogenic researchers now generally agree that a small number of critical chemical imperatives had to have been realized for organic life to have arisen. Among these are the very early production of short polymers of amino acids (Lahav, Nir, and Elitzur 2001; Rode 1999). Critically, a subpopulation of these peptides would have needed to possess the ability to catalyze not only their own construction but also a host of different types of chemistries. We now turn our attention to these self-replicating catalytic peptides (SRCP) and how they might have arisen.

GENERATION OF SELF-REPLICATING CATALYTIC PEPTIDES

Our discussion starts with a brief review of basic concepts in amino acid and peptide chemistry. Amino acids are the building blocks from which peptides and proteins are built. Each of the twenty naturally occurring amino acids possesses a carboxylic acid and an amine functionality that allows them to enter into chemical reaction to form polymers. Under the direction of a cell's protein-building machinery, the amine of one amino acid will be chemically linked to the carboxylic acid of another amino acid to form a peptide bond between them. Continued sequential coupling of amino acids to the growing polymer will first produce short peptides, usually defined as two to twenty amino acids in length, and ultimately long protein strands often comprising many hundreds of amino acids. Each amino acid also possesses a "side-chain." The side-chains of the twenty amino acids differ from one another and impart to each amino acid a particular type of chemical reactivity.

A challenge of prebiotic chemical research is to understand how peptides and proteins could have first arisen in the absence of appropriate cellular machinery. The generation and function of SRCPs is a problem in chemical mechanism and dynamics and perhaps is best understood with the aid of a diagram of the sort one often uses in explaining and representing chemical processes. Figure 1 contains such a diagram and depicts the generation and function of an SRCP. In this scheme, the SRCP is molecule A-B, which is shown to arise from a specific reaction of precursor

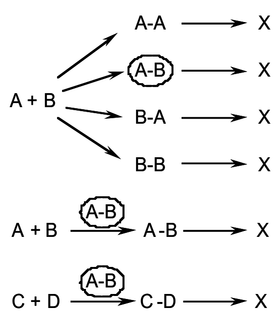

Fig. 1. Generation and function of the SRCP A-B. Progenitor molecules A and B can react to form four possible peptides, only one of which has catalytic properties of an SRCP. A-B catalyzes its own construction as well as formation of C-D. Peptides break down to decomposition materials X, which may or may not be able to form progenitor molecules. This scheme uses standard chemical notation in which each of the capital letters corresponds to a molecule, in this case progenitor amino acids or short peptides. Arrows correspond to chemical reactions and can be read as "yields." Thus, the chemical phrase A + B —> A-B should be read "molecule A and molecule B combine during a chemical reaction to yield reaction product molecule A-B."

molecules A and B, which may be either peptides or amino acids. Chemical reaction of such precursor molecules to form elongated peptides is called *ligation* and can generate the four end-to-end combinations that are shown. In this scheme, we assume that only one of these four products, A-B, has catalytic properties required of an SRCP: the ability to catalyze its own construction and the ability to catalyze production of other peptides. Each of the four ligation reactions proceeds at a rate that is a function of at least three properties: (1) chemical reactivities of the four reactants (A, B, C, and D); (2) efficiency of catalysis by A-B, which may differ for the two reactions it catalyzes; and (3) environmental conditions that exist during reaction. Also illustrated in Figure 1 is the inevitable instability of all ligation reaction products, all of which are shown to decompose to some molecule X.

Using the chemical mechanism of Figure 1, reaction progress curves were simulated for the time-dependent production of A-B and C-D. These are shown in Figure 2 and illustrate a number of important principles. The production of A-B is characterized by a long lag phase in which its concentration does not significantly increase until a critical concentration of A-B is achieved to catalyze its own production. This is the hallmark of any SRCM. Once the critical concentration of A-B is reached, its production enters a period of exponential growth until progenitor molecules are consumed. Finally, the concentration A-B declines with time due to the inherent chemical instability of all molecules, eventually going to zero. In broad strokes, the production of C-D will mirror that of A-B. There is a longer lag phase because A-B must accumulate before it can significantly

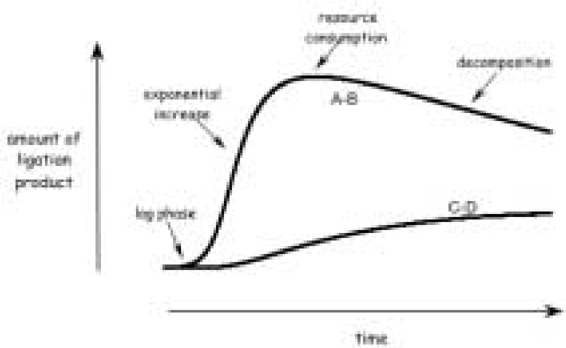

Fig. 2. Simulated time course for the production of A-B and C-D according to the mechanism of Figure 1. In this simulation, the following three conditions were set: (1) rate constants were set equal for the four ligation reactions of A and B, (2) catalytic self-replication of A-B was set twenty times more efficient than A-B–catalyzed formation of C-D, and (3) rate constants for all decomposition reactions were set equal. The four phases of the reaction time are indicated and discussed in the text.

catalyze formation of C-D. Resource consumption limits how much C-D will form. Finally, C-D concentration will in fact also go to zero.

It is clear that production of A-B in quantities to be of any catalytic use depends not only on its catalytic efficiency but also on the relative rates of "critical-path" and "off-path" reactions. The former includes the two reactions that lead to A-B, while the latter include production of competing molecules A-A, B-A, and B-B, and decomposition reactions.

In this simulation, the rate constants[1] were set in just such a way as to allow A-B to accumulate, thus allowing me to illustrate the function of A-B. But, of course, this needn't have been the case during the actual spontaneous generation of peptides four billion years ago. It could very well have been that the relevant rate constants were of such a magnitude as to prohibit SRCPs from ever accumulating. We return later to again consider these rate constants and how they must have been "balanced," but at the moment let us turn our attention to the question of what the likelihood was that SRCPs arose spontaneously. I do not believe I would be incorrect in saying that this likelihood was small. But I want to go a step farther and say, at least for the sake of the argument of this essay, that the probability of SRCPs arising spontaneously was precisely zero, *if* our world is the materialistic world of modern science, of unchanging, nonexperiencing substance. In the next section I propose the sort of universe that must obtain for SRCPs to arise.

A Universe in Process—Panentheism, Panexperientialism, and the Generation of Self-Replicating Catalytic Peptides

An underlying assumption of this article, implicit in the previous discussion, is that prebiotic chemistry is knowable. Primal amino acids, the first SRCPs, and even the first cell-like structures all arose by a series of chemical reactions that are in principle knowable. Further, if these reactions could be enumerated, they would all be quite unremarkable in the sorts of chemistries they reflect. But what is remarkable, and I believe staggeringly so, is that these reactions occurred in just the right order and with just the right inhibition of side reactions to allow the generation of SRCPs with just the right properties and in the just the right amounts. "Remarkable," of course, is in the eye of the beholder. Some would argue that while the formation of SRCPs and then the first cell might be unlikely, it nonetheless merely reflects the outworkings of a materialistic universe. But the molecules of such a universe are mere machines and incapable of subjective experience and relation. In a world of vacuous entities, can chemical evolutionary development occur? I argue here that it cannot and go on to suggest an alternate worldview, one that supports the formation of SRCPs.

Evolution as Self-Transcendence and Teleologic Response. In the evolution of life,[2] we see "self-transcendence [and the] amazing capacity to go beyond what went before" (Wilber 2000, 20). Atoms bond into inorganic chemicals, which rearrange and join to form organic molecules, which polymerize into SRCMs and other prebiotic macromolecules, which organize into suprastructures and the first protocellular forms. Life emerges from the cosmos. But how is this possible? Why is it that life comes to be in this universe?

In Whitehead's philosophy of organism we have a starting point for the development of an answer. Whitehead wants us to understand that

> a thoroughgoing evolutionary philosophy is inconsistent with materialism. The aboriginal stuff, or material, from which a materialistic philosophy starts is incapable of evolution. . . . There is nothing to evolve, because one set of external relations is as good as any other set of external relations. There can merely be change, purposeless and unprogressive. [Evolution] requires an underlying activity—a substantial activity—expressing itself in individual embodiments. (Whitehead [1925] 1967, 107)

Evolution is the progressive advancement of subjects and reflects an underlying creativity that cannot be explained by an ontology of vacuous material substance. "Nuts and bolts cannot evolve! They can only be rearranged" (Birch 1998, 71). Evolution occurs by changes in the internal relations of the subject as they are influenced by the environment. The potential for self-transformation and self-transcendence that *is* evolution is actualized as teleologic response, where teleology can be seen as the present, with the seeds of its future bound up in it, actualizing its potential. Teleology is "the process by which the immature becomes mature in terms of the systematic whole that is being generated" (Harris 1970, 70–71).

Teleology, of course, carries with it another sense—in which goals influence unfolding of the present. This is reflected in the "initial aim" of Whitehead's ontology. "[God] is that actual entity from which each temporal concrescence receives that initial aim from which its self-causation starts" (Whitehead [1929] 1978, 244). In his philosophy of organism, initial aim is the means by which God influences, but not determines, the outcome of all the world's processes, the becoming of all "actual entities," where the actual entities constituting reality must be seen not as static substance but rather as participating in a dynamic process of becoming. Importantly, God as actual entity is not removed from reality but is part of reality. Whitehead explains that "God is not to be treated as an exception to all metaphysical principles. . . . He is their chief exemplification" ([1929] 1978, 343).

Material Substance and Process. Process thought, as a metaphysical system, focuses principally on change and the temporal. Becoming, not being, is ontologically central. Contingency, emergence, and creativity are essential elements and take precedence over determinism and the static. The basic unit-events of the world, "actual occasions of experience," are not vacuous but rather possess a subjective nature that allows them attributes that might be called "feeling," "memory," and "creativity." But how can process, and not material substance, constitute reality? To answer this question, we need to better understand the difference between the fundamental claims of substance ontology and process ontology.

According to substance ontology, reality comprises material substance—static and nonexperiencing. Material substance has an objective nature only, lacking both subjective and temporal natures. That is, material substance is not only incapable of enjoying experience, it also does not change through time. In substance ontology, processes rearrange matter, and, since matter lacks a subjective nature, processes happen *to* matter. In contrast to this is process ontology, according to which reality comprises process—dynamic and capable of experience. Processes have an objective nature (that is, processes can be experienced by subjects), a subjective nature (processes can experience, are partly self-determining, and can enter into relation with other processes), and a temporal nature (processes happen through time or, perhaps, define time). Thus, enduring material substance is mere appearance and exists as stable patterns established by sequential processes. To quote Nicholas Rescher, "process philosophers tend to be realist about processes but idealist about substances" (1996, 58).

The Panentheistic God of Process Thought and the Becoming of Actualities. Process thought rejects concepts of a distant, unengaged God in favor of a God that is everywhere present in the universe and experiences the universe. This is through and through a panentheistic ontology (Clayton and Peacocke 2004) and gives us a first hint as to how God is able to act in the world by virtue of God's immanence in it (Peacocke 1993, 157–60). In all panentheistic ontologies, the universe is said to be contained within God. Such theologies are motivated by the desire to explain the simultaneous experience of God's immanence and transcendence.

This belief is found in many of great religious traditions of the world. In Hinduism, which has been informed by millennia-old Indian philosophical thought, we find the teaching that the Self is intimately associated with the Absolute. This is expressed in the Chandogya Upanishad, the most ancient of the Upanishads, which proclaims: "*Tat tvam asi*," That art thou (Radhakrishnan and Moore [1957] 1989, 69). These thoughts are the substance of a panentheistic concept of God, in which we and all that is have our existence as a "part" of God's being. Also, in Christianity we can see a panentheistic God. Paul quotes the philosopher-poet Epimenides and tells us of the human quest for God: "They would search for God and perhaps grope for him and find him—though indeed he is not far from each one of us. For 'In him we live and move and have our being'" (Acts 17:27–28 NRSV).

It has been argued that panentheism is not only consistent with humanity's experience of God but is what ultimately *allows* for the experience of God (Borg 1997, 32–54; Peacocke 1993, 157–60).

In process thought, God experiences the world, and these experiences condition God's response to the world. This is summed up in Whitehead's statement that God's "derivative nature is consequent upon the creative advance of the world" ([1929] 1978, 345) and allows David R. Griffin to develop the concept of "variable divine influence" (2001, 144–48). Divine experience of the world must be a central concept in any construal of divine action that seeks coherence, for how can God act in ways that are relevant to the present state of the world if God does not know the present state of the world? (Cobb 1965, 179–86; Griffin 2001, 151) There must exist a "reciprocal relation" between God and the world: "What is done in the world is transformed into a reality in heaven, and the reality in heaven passes back into the world. By reason of this reciprocal relation, the love in the world passes into the love in heaven, and floods back again into the world. In this sense, God is the great companion—the fellow suffer who understands" (Whitehead [1929] 1978, 351).

Similar sentiments can be found in other contemporary Christian theologies. In Openness theology (Pinnock et al. 1994; Pinnock 2001), God lives in time and responds to the events of history (Pinnock 1994, 117–18). Even more significantly for humanity's relation with God, God suffers with us. "God has chosen to be open to the world and to share in its suffering because of his love" (Pinnock 1994, 188). John Macquarrie's existential theology allows for symmetry and reciprocity in the relation of God and the world: "God cannot be conceived apart from the world, for it is his very essence (letting-be) to create; God is affected by the world as well as affecting it, for creation entails risk and vulnerability; God is in time and history, as well as above them" (1977, 121).

The God of process thought influences the outcome of all events, shaping the becoming of all entities. In Whitehead's philosophy of organism, initial aim is the means by which God influences, but not determines, the outcome of all the world's processes, the becoming of all actual entities. We see then that the becoming of all occasions of experience is shaped by three factors: the past through prehension, its own efficacy of self-determination, and the initial aim of God. It is significant that although God has influence over all processes of the universe, "luring" them into the future, every event still has power to exert its own creative influence on its future. Whitehead's cosmos is characterized by the "creative advance into novelty" that is conditioned by the world and by God.

Whitehead tells us that "God is that actual entity from which each temporal concrescence receives that initial aim from which its self causation starts" ([1929] 1978, 244). Importantly, God as actual entity is not removed from reality but is part of reality. Whitehead explains that "God is not to be treated as an exception to all metaphysical principles. . . . He is their chief exemplification" ([1929] 1978, 343).

But how is it that God and the world interact? By what mechanism does the "causal joint" operate? This is explained, at least in part, by panexperientialism.

Panentheism/Panexperientialism as the Causal Joint between Creator and Creation. Perhaps the most intriguing feature of Whitehead's philosophy of organism is that we find subjects where we thought there existed only objects. The process doctrine that captures this thought is *panexperientialism*, the metaphysical proposition that all actual entities are experiencing entities. Panexperientialism describes a view of reality in which entities at all levels of complexity are capable of enjoying some degree of subjective experience. Whitehead explains that each actual occasion arises, in part, by "prehending" or absorbing data that is offered by the world around it. All actualities, whether a human or a cell or a molecule, are centers of experience.

Of course, only high-level actualities (humans, for example) have *conscious* experience; low-level actualities (such as cells and molecules and atoms) do not. For most actualities, "experience" simply means that they have the capacity to respond to their environment. We see that all actualities, and not just conscious beings, enjoy experience. In Whitehead's words, "Consciousness presupposes experience, and not experience consciousness" ([1929] 1978, 53).

A misunderstanding that often arises in discussions of panexperientialism is the notion that panexperientialism ascribes subjective experience to *all* the things of our world. This is not the case. Panexperientialism differentiates between aggregates, such as garbage heaps, rocks, and chairs, which do not experience, and "compound individuals," such as atoms, molecules, cells, and people, which do. The distinguishing feature of a compound individual is that it responds to stimuli as a unity (Griffin 2001, 120–26).

Another important component of panexperientialism is the concept that actualities at one level can give rise to higher-level actualities (Griffin 2000, 101). This concept is based on the idea that an actual occasion of experience, during its formation, prehends or absorbs some aspect of all other actual occasions and, as this entity dissolves away, it is likewise absorbed by entities that are then forming. As Griffin explains, it is this that allows mind to emerge from the working of brain cells: "The mind is a series of very high-level occasions of experience, each of which unifies the myriad data received from the many brain cells into a subjective unity of experience" (Griffin 1989, 89).

Thus, panexperientialism offers a solution to the mind-body problem by allowing a form of perception that is not limited to sensory perception. Sensory perception is a high-level property, derived from a more fundamental, nonsensory perception, which Whitehead and Griffin call "physical prehension," a feature that is shared by all actual entities (Griffin 2000, 102). Thus, mind and the cells of the brain interact by prehending each other's experiences.

This solution to the mind-body problem, together with a doctrine of panentheism, can serve as a model not only for how humans can experience God but also how God acts in the world. Concerning the former, each of us has within us the ability to apprehend a reality that includes God at a preconscious and prereflective level (Stein 2002; Cobb and Griffin 1976, 31–32). Even though God is not a possible object of our senses, we directly prehend God, just as our brain cells prehend our minds. When these prehensions rise to the level of our consciousness, they become divine or mystical experience. The other side of the experience of God by humans is divine action in the world. God is not only immanent in the world, but God's immanence can have dynamic manifestation. God is able to act in the world by virtue of the fact that God is a "living person—an everlasting personally ordered society of divine occasions of experience" (Griffin 2001, 156) and thus can be prehended by the atoms, molecules, and people that populate the world.

At first blush, this panentheism/panexperientialism connection appears to hold the key for understanding how the first SRCPs arose. If the universe is part of God, and if the molecules that populate the universe are capable of enjoying subjective experience, it seems straightforward enough to posit that this relationship allowed God to "direct" the chemistry that was required to produce SRCPs and ultimately the first cell-like structures. "Whiteheadian panentheism, with its panexperientialism, allows us to develop a theistic evolutionism, according to which the evolutionary process has been significantly directed by divine influence" (Griffin 2000, 103).

But this hypothesis, while consistent with theistic intuitions, is unsatisfying from a scientific perspective in that it does not address obvious chemical concerns that must be attended to if this hypothesis is to have sound scientific as well as metaphysical underpinnings. Specifically, what we need is a chemically informed hypothesis for how God interacts with the molecular world and in so doing worked within nature to bring about the first SRCPs. This hypothesis must suggest a mechanism by which rate constants for the critical-path reactions and the many off-path reactions are balanced to allow generation of SRCPs and, furthermore, must obey thermodynamic laws (such as conservation of energy) and chemical principles. Such a hypothesis is developed in the following section.

Chemical Evolution as Divine Motivation of Molecular Becoming

Emergence of Catalytic Peptides and Molecular Teleology. In his analysis of origins-of-life research, Lahav remarks that "the catalytic activity of linear peptides cannot be accounted for by a simple combination of the relevant properties of their constituent amino acids" (Lahav, Nir, and Elitzur 2001, 85). This is a most profound observation. Lahav has expressed one of the central features of a process ontology of chemistry (Stein 2004; 2006): that the essential nature of the compound subject transcends, and cannot be reduced to, the simples from which it is composed. The first SRCP possessed unprecedented functionality, inherent only in the relational properties of the whole, that could be expressed only upon combination of certain amino acids. If we imagine these peptides embedded in a complex evolutionary holoarchy[3] of biologic catalysis, we see them transcending their constituent amino acids, which themselves have properties surpassing their atomic composition, and being subsumed by enzymes and then higher-order biological catalysts and metabolic pathways. In this holoarchy, we also see a molecular teleology at work in which the potential possessed by amino acids to polymerize into forms with catalytic activity is actualized.

In the context of process thought, the emergence of catalytic capabilities is explained by first viewing the molecule as process, or, in Whitehead's technical vocabulary, a structured society of actual occasions of experience ([1929] 1978, 99), "an historic route of actual occasions" ([1929] 1978, 80). In this construal, a molecule possesses an identity not because it is static and unchanging but because it is a dynamic system exhibiting a stability pattern through time (Rescher 1996, 99). Catalytic capabilities finally emerged in certain peptides as a result of a long process of molecular evolution that involved untold numbers of molecular interactions and reactions, where these reactions are "the consequential differences in the actual occasions" (Whitehead [1929] 1978, 80) that make up the particular structured society that defines each of the reacting molecules. Molecular evolution occurred in response to both internally derived creative impulses that are possessed to some extent by all entities as well as God's initial aim which provides divine motivation to each of the serially ordered occasions of the many molecular societies.

Molecular evolution is a synthesis of the two types of teleology previously discussed: teleology as *potential* actualized as the present unfolds and teleology as *goals* influencing the unfolding of the present. Molecular evolution is necessarily a synthesis of these two types of teleological impulse because it is only with the aim of God toward the goals of life and consciousness that the present will unfold to maximize molecular potential. The initial aim of God will be always to maximize complexity, novelty, and value in the world (Whitehead [1929] 1978, 346). SRCPs arose as a consequence of the divine lure toward complexity, novelty, and ultimately life.

Now, on a chemical level, this would have been played out as an adjustment or fine-tuning of rate constants to favor production of SRCPs and to inhibit off-path and decomposition reactions. This concept is illustrated in the simulation of Figure 3, where a fine-tuning of rate constants relative to the situation of Figure 2 results in very dramatic changes in all phases of the production of A-B.

The previous analysis addresses the *what* of divine motivation of chemical evolution but not the *how*. This is the critical issue to which we now turn.

Energy, Causation, and Becoming. We have identified the causal joint as an immanent God acting through a world of panexperiential entities. But how does God "flex" the causal joint? By what means could God have adjusted rate constants of the chemical reactions that were occurring in some warm little pond four billion years ago? We are asking here the Ultimate Question of divine action in the world. To answer it, we must first understand Whitehead's notion of energy and how the flow of energy defines reality. This emphasis on energy is necessary because, as we will see, the rates at which molecular transformations occur are entirely dependent on the energy content of and distribution within molecules.

According to process thought, pulsing through every entity and event is a complex energy that is purposive and creative. It is from this complex energy, which drives the unfolding of the processes of all occasions, that the physicist abstracts his "energy."

> The science of physics conceives a natural occasion as a locus of energy. Whatever else that occasion may be, it is an individual fact harboring that energy. . . . [P]hysical science recognizes qualitative differences between occasions in respect to the way in which each occasion entertains its energy. These differences are entirely constituted by the flux of energy, that is to say, by the way in which the occasions in question have inherited their energy from the past of nature, and in which they are about to transmit their energy to the future. (Whitehead [1933] 1967, 185)

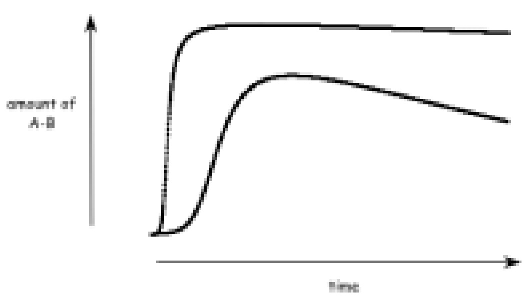

Fig. 3. Simulated time courses for the production of A-B according to the mechanism of Fig. 1. The bottom curve comes directly from Fig. 1, while the upper curve reflects a situation in which the rate constants for A-B production and decomposition were subjected to fivefold increases and decreases, respectively. These adjustments result in a decrease in the lag phase and increases in the exponential growth of A-B and final amount produced. This simulation illustrates how a simple adjustment of critical rate constants can lead to the favored formation of SRCP A-B.

Whitehead's central concern here is how the flow of energy fundamentally defines the becoming of all occasions. This theme has been amplified by Marjorie Hewitt Suchocki, who tells us that in the becoming of an entity, "each element of existence draws from the transmitted energies of its past, combining these energies in a creative moment toward its own actuality" (1997, 12). To become is be a nexus of energy flow.

But this raises the specter of energy/entity dualism: How is energy, if it is distinct from entity, transmitted among entities? Light is shed on the mechanism of energy flux among entities by understanding that "mass is energy" (Einstein and Infeld 1938, 244). In formulating the equivalence of mass and energy, Einstein tells us that the universe is made of a single stuff, and this stuff is energy: "matter is where the concentration of energy is great" (1938, 242). Suchocki provides a valuable insight that helps us understand the equivalence between mass and energy as it relates to becoming: ". . . all of space is permeated with radiant energy that is made up of a series of many units. In concentrated configurations, these units become particles of matter; in increasingly larger groupings of these particles, they become items familiar to human experience . . . *each unit is the reception, unification, and transmission of energy*" (Suchocki 1997, 237–38; emphasis added)

The universe is made of a single stuff. And with this realization, energy/entity dualism dissolves into monism. But this is not a featureless monism; this monism possesses a threefold internal relationship that unites energy, causation, and becoming. Energy has an equivalence link to causation; it would not be a mistake to equate energy with causal propensity. And energy/causality is that which drives and is simultaneously transmitted during the becoming of all actual occasions. *Energy is the causal ground of becoming of all occasions.* Thus, God as actual entity can be said to provide the divine initial aim, as a transmission of energy, to all actual occasions. To paraphrase Paul Tillich, God is the ground of causation of the becoming of all that is.

Now, let us once more consider the molecule and its reactions, first as chemists and then through the lens of process thought. Combined, these explanatory vehicles will allow us to finally construct a hypothesis for how God interacts with the world.

A molecule typically can undergo a great many types of chemical reactions, each reaction occurring at a particular rate and producing a distinct set of products. Chemists call this pattern of behavior the chemical reactivity of a molecule. Chemical reactivity is a function of molecular properties including the total energy content of the molecule and how this energy is distributed among the several chemical bonds that exist between the atoms of the molecule. Energy content and distribution is dependent not only on details of the atomic composition of the molecule but also on the environment in which the molecule finds itself. And, finally, the rates at which the various transformations that a molecule can potentially undergo are a function of the molecule's energy content as well as the distribution of this energy. Chemical bonds in a molecule that have a high energy content will react faster than low-energy bonds that are otherwise chemically equivalent.

This view of chemical reactivity, while informative and accurate in a utilitarian sense, is informed by an ontologically shallow metaphysic of materialism. Although such notions of material substance "expresses a useful abstract for many purposes of life" and have a "sound pragmatic defense" (Whitehead [1929] 1978, 79), reliance on such an ontology gives a deficient and impoverished view of reality, offering precious little room for understanding divine action. For this, we need a process metaphysic of chemical reactivity.

The molecule, as a structured society of actual occasions of experience, is defined by relation, both internal and external. Molecular entities are not mere objects, vacuous entities, but rather can be said to possess a subjective nature that allows them to experience and respond to their environment (Stein 2004; 2006). Such an ontology is necessarily based on a panexperientialist understanding of nature in general and molecules in particular:

> When we think of a molecule as a nonexperiencing thing, we are thinking of it as experienced by us. . . . We do not experience what it is to be a molecule. We only know it, insofar as we know it at all, from without. . . . To assume that some things without any experience exist would be a category mistake. . . . To say that a molecule has experience means only that it has some vague feeling-response to its environment. . . . The molecule need not be thought of as simply an aggregate of atoms. Insofar as a molecule shows signs of responding to its environment with a unity of action, it can be thought to have a unity of experience. The idea that each atom can receive feelings from the molecular experiences explains how the whole molecule can act as a unity. (Griffin 1988, 151–58)

These relational experiences occur as a transfer of energy, defining the molecule's becoming and producing a spectrum of causality that manifests as a spectrum of transformations that the molecule undergoes. For a particular molecule, certain combinations of internal atomic experiences and external environment-conditioned experiences will produce a specific pattern of energy/causality within the molecule, motivating a specific type of transformation. Transformations that occur rapidly, and are said by chemists to reflect chemical bonds of high energy content, are those that have acquired, from their experience of internal and external relation, a more intense causal propensity. We now can see that a molecule's chemical reactivity is underwritten by an ontology of relational becoming in which *energy is the causal ground of molecular transformative process*.

Once more, think about the reactions that molecules A and B can undergo according to Figure 1. We have seen that the distribution of possible products is dictated not only by the chemical natures of A and B but also by the environment, meaning that certain conditions will favor the production of A-B over the other three potential reaction products. We can now analyze this chemical phenomenon in the context of a process ontology of molecular becoming.

Molecular entities A and B each has its own individual path of becoming, each path defined by internal and external relation. Not only do A and B have temporal natures, but they also have spatial natures; A and B both are extensive and thus exist in some spatial relation to one another. When the spatial relation between A and B places them at a specific, critical distance from one another, causal tendencies of the system that A and B compose undergo a dramatic change. Where once causal tendency engendered mere repetition in A and B as individuals, causal tendency now takes a turn toward novelty, engendering an ontologic fusion of A with B to form something new. Of the four possible molecular entities that can potentially emerge from this fusion of A and B, the one that forms most rapidly is the one for which the route of passage is causally unobstructed, where particular portions of A and particular portions of B are in intimate relation and where these extensive aspects of A and of B possess the greatest causal intensity toward novelty rather than toward repetition.

In the above discussion, the philosopher's "causal tendency" and "causal intensity" have replaced the chemist's "energy" and gradations of energy. In reality, both are linguistic placeholders for an ontologically deeper level about which we have little understanding. Both kinds of vocabulary express, in different ways, a mere recognition that we live in a world of causation. Both philosophers and scientists struggle to understand why it is that events happen and must have causes.

Divine Action: God Acts in the Molecular World. This description of molecular transformation with its ontologic foundation set in process thought provides the understanding that is necessary to construct a hypothesis for how God works within the molecular world and thereby was able to bring forth the first SRCPs. I propose that God's action within the molecular world has its origin in God's ability to alter the energy distribution within a system of reacting molecules in such a way as to favor a specific set of reaction products. This altered energy distribution and resultant change in chemical reactivity constitute and define the divine initial aim that is received by this molecular system as a structured society of occasions of experience. This is the "lure" toward novelty and value that God provides as part of the becoming of all occasions of experiences.

To understand how God accomplishes this, we need to draw on our previous analysis of the intimate relationship between energy and causation and how this, in turn, is related to God. We came to see that energy *is* causal propensity, and in a world of process, energy, as causation, can be seen to undergird the creative becoming of all occasions of experience. These ideas find support from concepts of contemporary physics that inform our understanding of reality and tell us that the material things of this world are, in fact, energy events. God is able to interact with our world because God too is an energy event: "If what is most real are energy-events, and if these are highly diverse in their character, then God can be conceived as a very special kind of energy-event" (Cobb [1965] 1998, 71). This thought reflects a basic premise of process theology—that God is not to be considered an exception to the metaphysical principles of our universe but rather "He is their chief exemplification" (Whitehead [1929] 1978, 343).

The idea that God is in some sense an energy event can be found in other strands of contemporary theology as well. Wolfhart Pannenberg's vision of the spirit of God as a "universal field of energy" (1993, 132) motivated Keith Ward to suggest that "Within the perspective of modern cosmology, one might see God not as an intervener from outside a closed deterministic system, but as a total field which sets the goals of the cosmic process and continuously influences events towards their goals" (1996, 298). The elusive causal joint between Creator and creation can now be seen to be an energy that defines and constitutes all that is actual. The flexing of this joint occurs as transduction of this energy.

God's mode of interaction with the world, involving energy transduction at the molecular level, may also help us understand the mind-body problem discussed earlier. Again, consider Griffin's argument that body and mind are of the same kind:

> The apparent difference in kind between our experience, or our "mind," and the entities comprising our bodies is an illusion, resulting from the fact that we know them in two different ways: We know our minds from within, by identity, whereas in sensory perception of our bodies we know them from without. Once we realize this, there is no reason to assume them really to be different in kind. (Griffin 2000, 169)

Because mind and bodies are of the same kind, they can communicate. But this is only a partial solution to the mind-body problem. It seems clear that neuroscientists and philosophers of mind need to consider events that occur at the molecular level if progress is to be made in formulating a truly comprehensive solution to the mind-body problem. When my conscious self instructs my fingers to type these words, the firing of the first neurons at the neuronal/muscular junctions occurs because certain neurotransmitter molecules are released in response to a series of molecular events. So the question that is typically asked, How is it that mind is able to cause my fingers to move?, should be replaced by How is it that mind is able to cause specific, finger-moving molecular events to occur rather than other molecular events? The answer is that self changes the distribution of energy in molecules that participate in the desired bodily action. As we gain an understanding of this, we may also gain further understanding of how God interacts with the world.

From a strictly chemical point of view, there is nothing remarkable about this sort of mechanism in which a molecular system's reactivity is altered by a redistribution of energy. For example, it is now standard methodology in the field of photochemistry to be able to selectively "energize" particular bonds in a molecule to favor certain reaction products (le Noble 1974; Bochet 2000). Complex organic molecules can be irradiated with light of a specific wavelength (that is, light of a specific energy content) that selectively excites, or energizes, only those bonds within the molecule that are able to absorb the energy of this wavelength of light. Once energized, these bonds, and only these bonds, undergo chemical reaction.

Likewise, the transduction of energy from one site to be utilized at another site is just how enzymes are thought to effect catalysis. Enzymes are protein molecules that are able to greatly accelerate critical biochemical reactions. Enzymes are thought to catalyze their reactions via a mechanism in which they transfer, or more correctly transduce, energy that is available from the aqueous environment to a specific locus on its surface, known as the active site, where molecular transformation of substrate to product occurs at a rate that is often billion of times faster than the rate in the absence of enzyme (Stein 2004; 2006; Welch 1986). The enzyme transduces heat and collisional energy of the environment to a small localized area on its surface to energize molecules that are bound to it in such a way as to bring about specific reactions while inhibiting other reactions.

The proposed mechanism of divine motivation of molecular becoming, then, is consistent with chemical principles and violates no physical or thermodynamic laws such as the conservation of energy. The latter point is particularly important. Any detailed mechanistic proposal for how God acts in the world that wishes to be taken seriously from a scientific perspective must address the issue of how God acts in the universe without adding energy to the universe. Creation of new energy in a closed system such as our universe is forbidden by thermodynamic laws. However, transfer of energy and transduction of energy from one form to another is allowed and is precisely what is being proposed here for the mode of God's action in the world.

Final Thoughts

It may be that we will never fully understand how life arose on our planet. Happening so long ago in an environment that we can hardly imagine, it is difficult to construct hypotheses that are comprehensive, let alone testable. Nonetheless, we may eventually be successful and formulate abiogenic theories that have broad explanatory power. But if these theories are underpinned by a substance metaphysic, they will not have incorporated critical features of reality.

Ivor Leclerc clearly saw this and explained that only through the development of new metaphysical theories would new ways emerge for understanding the reality that is revealed by science. "Indispensable in the future will be the formulation of alternative theories of nature as bases for alternative interpretations of scientific evidence. Through such interpretations the philosophical theories will be tested, and the scientific evidence understood" (Leclerc 1972, 15–16).

I believe that process thought offers a way of seeing reality that allows a fuller understanding of our world. In this essay, I have used process thought as my backdrop as I explored the origins of life. It allows a hypothesis to be developed that at once satisfies our deep intuitions of teleology and our scientific sensibilities. I have proposed a model to explain how God could have worked in the primal world to lure inorganic matter toward ever greater complexity and novelty that is chemically and thermodynamically sound. I also have suggested a model for divine action in which the causal joint that exists between God and universe is an energy flux between God and molecule. God's action in the world is divine motivation of chemical becoming.[4]

NOTES

1. A "rate constant" is a numerical quantity that reflects the speed with which a chemical reaction occurs. Efficient and rapid reactions are associated with large rate constants.
2. Often the term *evolution* is used in a restricted sense to refer only to the biological process by which advanced multicellular life forms developed from the first cell. In this essay I impose no such restriction but instead use this term to refer to the entire process that started with the abiogenic formation of the first cell.
3. The term *holoarchy* is part of a useful descriptive apparatus developed by Ken Wilber (2000) in which particular elements of reality are seen as constituting parts of a relational set of nested or concentric elements. Although Wilber traces the idea to Arthur Koestler (1978), who coined the term *holon* to refer to an entity that is simultaneously a whole and a part of some other whole (Wilber 2000, 17), similar thinking appears in the work of Ivor Leclerc (1972, 311) and process thought in general (Rescher 2000, 30–32).
4. It is important to note that this may not be the only mode of interaction between God and the universe. In addition to the mechanism described here, it has been proposed that God may act by means related to the quantum indeterminacy of microsystems (Russell et al. 2001) or to the chaotic behavior of macrosystems (Russell, Murphy, and Peacocke 1997). Of course, all proposals to explain divine action will inevitably suffer from some degree of incompleteness and approximation, for how can humans achieve a complete understanding of the means by which God acts in the universe? Nonetheless, work in this area should continue, and a fruitful path forward in our attempts to understand divine action may indeed be found in exploring relationships among theories of molecular transformation, quantum mechanics, and chaotic behavior.

References

Birch, Charles. 1998. "The Postmodern Challenge to Biology." In *The Reenchantment of Science*, ed. D. R. Griffin, 69–78. Albany: State Univ. of New York Press.

Bochet, Christian G. 2000. "Wavelength-Selective Cleavage of Photolabile Protecting Groups." *Tetrahedron Letters* 41:6341–42.

Borg, Marcus J. 1997. *The God We Never Knew: Beyond Dogmatic Religion to a More Authentic Contemporary Faith*. San Francisco: HarperSanFrancisco.

Bunge, Mario. 1971. "Is Scientific Metaphysics Possible?" *Journal of Philosophy* 68:507–20.

Clayton, Philip, and Arthur Peacocke, eds. 2004. *In Whom We Live and Move and Have Our Being: Panentheistic Reflections on God's Presence in a Scientific World*. Grand Rapids, Mich.: William B. Eerdmans.

Cobb, John B. 1965. *A Christian Natural Theology*. Philadelphia: Westminster.

———. [1965] 1998. *God and the World*. Eugene, Or.: Wipf and Stock.

Cobb, John B., and David R. Griffin. 1976. *Process Theology: An Introductory Exposition*. Philadelphia: Westminster.

Crick, Francis. 1981. *Life Itself: Its Origins and Nature*. New York: Simon and Schuster.

Denton, Michael J. 1998. *Nature's Destiny: How the Laws of Biology Reveal Purpose in the Universe*. London: Free Press.

Einstein, Albert, and Leopold Infeld. 1938. *The Evolution of Physics: From Early Concepts to Relativity and Quanta*. New York: Simon and Schuster.

Griffin, David Ray. 1988. "Of Minds and Molecules: Postmodern Medicine in a Psychosomatic Universe." In *The Reenchantment of Science*, ed. D. R. Griffin, 141–63. Albany: State Univ. of New York Press.

———. 1989. *God and Religion in the Postmodern World*. Albany: State Univ. of New York Press.

———. 2000. *Religion and Scientific Naturalism: Overcoming the Conflicts*. Albany: State Univ. of New York Press.

———. 2001. *Reenchantment without Supernaturalism: A Process Philosophy of Religion*. Ithaca, N.Y.: Cornell Univ. Press.

Harris, Errol E. 1970. *Hypothesis and Perception*. London: George Allen & Unwin.

Kauffman, Stuart A. 1993. *The Origins of Order: Self-Organization and Selection in Evolution*. New York: Oxford Univ. Press.

Koestler, Arthur. 1978. *Janus: A Summing Up*. New York: Random House.

Lahav, Noam, Shlomo Nir, and Avshalom Elitzur. 2001. "The Emergence of Life on Earth." *Progress in Biophysics and Molecular Biology* 75:76–120.

Lange, Marc. 2002. *An Introduction to the Philosophy of Physics: Locality, Field, Energy, and Mass*. Oxford: Blackwell.

le Noble, William J. 1974. "Photochemistry." Chapter 13 in *Highlights of Organic Chemistry: An Advanced Textbook*. New York: Marcel Dekke.

Leclerc, Ivor. 1972. *The Nature of Physical Existence*. London: George Allen & Unwin.

Lee, Harold N. 1947. "Metaphysics as Hypothesis." *Journal of Philosophy* 44:344–52.

Macquarrie, John. 1977. *Principles of Christian Theology*. 2d ed. New York: Charles Scribner's Sons.

Martin, William, and Michael J. Russel. 2002. "On the Origins of Cells: A Hypothesis for the Evolutionary Transitions from Abiotic Geochemistry to Chemoautotrophic Prokaryotes, and from Prokaryotes to Nucleated Cells." *Philosophical Transactions of the Royal Society London B* 358:59–85.

Maurel, Marie-Christine, and Jean-Luc Decout. 1999. "Origins of Life: Molecular Foundations and New Approaches." *Tetrahedron* 55:3141–82.

Miller, Stanley L. 1953. "Production of Amino Acids under Possible Primitive Earth Conditions." *Science* 117:528–29.

———. 1955. "Production of Some Organic Compounds under Possible Primitive Earth Conditions." *Journal of the American Chemical Society* 77:2351–60.

Miller, Stanley L., and Harold Urey. 1959. "Organic Compound Synthesis on the Primitive Earth." *Science* 130:245–51.

Orgel, Leslie E. 1998. "The Origins of Life: A Review of Facts and Speculations." *Trends in Biochemical Sciences* 23:491–95.

Pannenberg, Wolfhart. 1993. *Toward a Theology of Nature*. Louisville, Ky.: Westminster.
Peacocke, Arthur. 1993. *Theology for a Scientific Age*. Minneapolis: Fortress.
Pinnock, Clark. 1994. "Systematic Theology." In *The Openness of God: A Biblical Challenge to the Traditional Understanding of God*, ed. C. Pinnock, R. Rice, J. Sanders, W. Hasker, and D. Basinger, 101–25. Downers Grove, Ill.: InterVarsity.
———. 2001. *Most Moved Mover: A Theology of God's Openness*. Grand Rapids, Mich.: Paternoster.
Pinnock, Clark, Richard Rice, John Sanders, William Hasker, and David Basinger, eds. 1994. *The Openness of God: A Biblical Challenge to the Traditional Understanding of God*. Downers Grove, Ill.: InterVarsity.
Radhakrishnan, Sarvepalli, and Charles A. Moore, eds. [1957] 1989. *A Source Book in Indian Philosophy*. Princeton: Princeton Univ. Press.
Rescher, Nicholas. 1996. *Process Metaphysics: An Introduction to Process Philosophy*. Albany: State Univ. of New York Press.
———. 2000. *Process Philosophy: A Survey of Basic Issues*. Pittsburgh: Univ. of Pittsburgh Press.
Rode, Bernd M. 1999. "Peptides and the Origin of Life." *Peptides* 20:773–86.
Russell, Robert John, Philip Clayton, Kirk Wegter-McNelly, and John Polkinghorne, eds. 2001. *Quantum Mechanics: Scientific Perspectives on Divine Action*. Vatican City: Vatican Observatory Publications.
Russell, Robert John, Nancy Murphy, and Arthur Peacocke, eds. 1997. *Chaos and Complexity: Scientific Perspectives on Divine Action*. Vatican City: Vatican Observatory Publications.
Stein, Ross L. 2002. "On the Possibility of an Immediate Experience of God." *Journal of Liberal Religion* 3 (2).
———. 2004. "Towards a Process Philosophy of Chemistry." *Hyle—International Journal for the Philosophy of Chemistry* 10:5–22.
———. 2006. "A Process Theory of Enzyme Catalytic Power: The Interplay of Science and Metaphysics." *Foundations of Chemistry* 8:3–29.
Suchocki, Marjorie H. 1997. *God Christ Church*. New York: Crossroad.
Sutherland, John D., and J. Nicole Whitfield. 1997. "Prebiotic Chemistry: A Bioorganic Perspective." *Tetrahedron* 53:11493–527.
Ward, Keith. 1996. *Religion and Creation*. Oxford: Clarendon.
Ward, Peter, and Donald Brownlee. 2000. *Rare Earth: Why Complex Life Is Uncommon in the Universe*. New York: Copernicus.
Welch, G. Rickey, ed. 1986. *The Fluctuating Enzyme*. New York: John Wiley.
Whitehead, Alfred North. [1925] 1967. *Science and the Modern World*. New York: MacMillan.
———. [1929] 1978. *Process and Reality*. New York: MacMillan.
———. [1933] 1967. *Adventures of Ideas*. New York: Free Press.
Wilber, Ken. 2000. *A Brief History of Everything*. Boston: Shambhala.