Profile: Conversations with John Polkinghorne

THE NATURE OF PHYSICAL REALITY

by John Polkinghorne

Abstract. This account of the dynamical theory of chaos leads to a metaphysical picture of a world with an open future, in which the laws of physics are emergent-downward approximations to a more subtle and supple reality and in which there is downward causation through information input as well as upward causation through energy input. Such a metaphysical picture can accommodate both human and divine agency.

Keywords: antireductionism; chaos; Bernard d'Espagnat; determinism; downward causation; emergence; Austin Farrer; Mitchell Feigenbaum; fractals; God of the gaps; Mandelbrot set; Donald MacKay; mechanism; mind and matter; Jürgen Moltmann; A. R. Peacocke; process thought; quantum theory; reductionism; A. N. Whitehead.

"There is no sense in which subatomic particles are to be graded as 'more real' than, say, a bacterial cell or a human person, or even social facts" (Peacocke 1986, 28). The words are those of that resolute antireductionist Arthur Peacocke, who in a series of writings has defended the existence of level autonomy in our descriptions of the physical world. Biology has its own concepts and understandings that are not reducible to complicated corollaries of physics and chemistry (Peacocke 1979, chap. 4; 1986, chaps. 1 and 2). I certainly agree that this is so (Polkinghorne 1986, chap. 6). Yet

John Polkinghorne is a former Professor of Mathematical Physics at Cambridge University, a Fellow of the Royal Society, and an Anglican priest. His mailing address is 74 Hurst Park Avenue, Cambridge, CB4 2AF, England. This article forms chapter 3 of Polkinghorne's book *Reason and Reality: The Relationship between Science and Theology* (London: SPCK, 1991, and Philadephia: Trinity Press International, 1991).

[*Zygon*, vol. 35, no. 4 (December 2000).]
 ISSN 0591-2385

it is hard indeed to dispel altogether from one's thinking a certain reductionist tendency. When we begin to consider the nature of physical reality it is instinctive to turn first to the insights of so-called fundamental science, to start with elementary particle physics and its spatially big brother, cosmology. Our discussion then becomes one of *emergence*; how, within physics itself and beyond it, new properties arise, such as the power of "classical measuring apparatus" to determine the outcome of uncertain quantum mechanical experiments; the ability of complex molecules to replicate themselves; the coming to be of consciousness, self-consciousness, worship. In fact, we understand very little of how these different levels relate to each other. The problems are mostly too hard for current knowledge, despite the stunning successes of molecular biology in casting light on the physical basis of genetics. But the direction in which to look for an understanding seems clear enough. It will come from being able to relate the higher level to the lower. Emergence is conceived as a one-way process, by which the higher whole arises from the complex organization of its lower parts.

The reasons for thinking this way appear clear enough. Vitalism seems dead, and even the most fervent antireductionist in relation to concepts, accepts a structural reductionism. Physical reality is made out of the entities described by fundamental physics: quarks and gluons and electrons (or superstrings, or whatever). Hence the feeling that if one day we wrote the equations of a Theory of Everything on our T-shirts, then we should have got somewhere, despite the fact that in terms of our actual understanding of the physical world those equations would be more like the precise statement of the problem, rather than its solution. Another encouragement to such a bottom-up way of thinking is that it recapitulates the way in which we believe the complexity of being to have come about. First there was the quark soup of the primeval universe; then nuclear matter after those famous first three minutes (see Weinberg 1977); then simple atoms when the background radiation was "frozen" out after about half a million years; much later the complex molecules in the shallow seas of early Earth; then unicellular life; then animals; then *Homo sapiens*. "Ontogeny recapitulates phylogeny," not only embryologically but also conceptually.

Yet it is possible that if subatomic particles are not "more real" than cells or persons, they are not more fundamental either. It is possible that emergence is, in fact, a two-way process—that it would be conceptually valid and valuable to attempt to traverse the ladder of complexity in both directions, not only relating the higher to the lower but also the lower to the higher. Such a proposal goes somewhat beyond the mere acknowledgment of level autonomy, for it suggests the existence of a degree of reciprocity of understanding between levels.

I am tempted to explore this notion because of a recent development in physics itself. I refer to that theory of complex dynamic systems that goes under the not altogether appropriate name of the theory of chaos (Davies

1989; Gleick 1988; Stewart 1989). It provides a perfect example of the fallacy of the "T-shirt approach" to understanding the world. Consider, for instance, the following simple equation relating a quantity, x_{n+1}, to its predecessor in the sequence x_n:

$$x_{n+1} = k.x_n \, (1 - x_n) \qquad (1)$$

The equation arises quite naturally in biological contexts, where the x's can be population sizes in successive years. Next year's population (x_{n+1}) depends upon how many of the species there are to breed this year (x_n) and on a factor which represents the attenuating effect of competition for limited resources if the population gets too big (here this factor is $(1 - x_n)$, where the variable x is a scaled population size chosen to make the equation look simple).[1] The proportionality factor k is a measure of how strong the coupling is of the population in one year to the combination of these two effects in the previous season. It is a parameter controlling possible growth rate.

If k is too small (less than 1), then x_n tends to zero with increasing n. The population is insufficiently fertile to maintain itself, and it dies out after a few years. We are dealing with an endangered species. Past that danger level, one might expect that the population for a given value of k would eventually maintain itself at a stable level, finely tuned to the available resources. For some values of k that is indeed the case. For example, if $k = 2$, the population may fluctuate for a few years, but it soon settles down to a steady $x = 0.5$. (Try it on a calculator, choosing some value of x at which to begin and seeing how quickly it homes in, after repetitions of the formula, to the value 1/2 .) However, beyond $k = 3$ that is no longer the case. For example, at $k = 3.2$ one finds that the population oscillates between two values; good and bad years alternate. That also is intuitively understandable, but the plot thickens after that. Once one gets above $k = 3.5$, the cycles rapidly complicate. First there is a fourfold cycle, then an eightfold, then a sixteenfold, etc. By the time you get to about $k = 3.58$ the population just jigs around in a completely random fashion, and no stable repeating pattern is ever established. We have entered the region of behavior that is called *chaotic*.

The moral of this mathematical tale is this: A simple and *perfectly deterministic* equation can produce behavior that is random to the point of unpredictability. The latter statement, however, demands explanation. When k is in the region corresponding to chaos, the behavior of x is immensely sensitive to the choice of starting value. Suppose one compares calculations starting with $x = 0.3$ and with $x = 0.3001$, initial conditions that differ by less than one part in a thousand. For a few repetitions of the calculation they will keep roughly in step, but quite soon the calculations will diverge from each other, giving totally different behaviors. It is characteristic of chaotic systems generally that unless one knows the initial circumstances with unlimited accuracy, one can only project their behavior a small way into the future with any confidence. Beyond that, they are intrinsically unpredictable.

It will not surprise you to learn that this feature of chaotic unpredictability first came to light during computer investigations of weather forecasting, using simple models of the behavior of the atmosphere. It gives rise to "what is only half-jokingly known as the Butterfly Effect—the notion that a butterfly stirring the air today in Peking can transform storm systems next month in New York" (Gleick 1988, 8). Yet there is also a contained randomness about the behavior of chaotic systems. They do not wander all over the place, but their motions home in on the continual and haphazard exploration of a limited range of possibilities (called a *strange attractor*). There is an orderly disorder in their behavior. That is why chaos theory was not a well-chosen name.

Similarly, there is a structure to the onset of chaos. Our discussion of equation (1) showed a cascading explosion of bifurcations: a twofold cycle branched to give a fourfold cycle, which branched to give an eightfold cycle, and so on, each branching following more rapidly on its predecessor. It was a capital discovery by Mitchell Feigenbaum that this behavior has a universal character. The precise way in which it happens is *not* a special property of equation (1) but is the same for all systems that become chaotic in this bifurcating fashion.[2] Here we see not only the emergence of order from chaos but also the emergence of universality from particularity. This is both a gain and a loss. One reaches widely applicable conclusions, but at the cost of losing power to probe the nature of the underlying mechanism. Ian Stewart comments that "Feigenbaum's discovery of universality is a two-edged sword. It makes it relatively easy to test a particular class of chaotic models; but it doesn't distinguish between the different models in that class" (Stewart 1989, 208).

A structure in which branches divide into subbranches, and so on forever, is an example of what the mathematicians call a *fractal*. Fractals are entities that look the same on whatever scale you examine them. Trees are approximately fractal. The way the trunk divides into limbs is very similar to the way the limbs divide into branches, which is very similar to the way the branches divide into twigs. Whether you look at the whole tree, or the twigs of a branch, the patterns are at least roughly the same. The most complicated entity known to the mathematicians is also approximately fractal. It is called the *Mandelbrot set*, after the Frenchman who first realized its astonishing fecundity. Its definition is comparatively simple to state mathematically (see Gleick 1988, 221–32; Stewart 1989, 236–41); its structure is inexhaustibly rich: whorls and dragon's claws made out of whorls and dragon's claws. Colored computer simulations of parts of the set are fascinatingly beautiful (Peitgren and Richter 1986). They have become favorite subjects for the covers of scientific books. There is enough to go round for everyone who wants to publish, since you have only to blow up part of an old pattern to reveal a new pattern, approximately similar but subtly different.

The general picture resulting from these considerations is that of deterministic equations giving rise to random behavior; of order and disorder interlacing each other; of unlimited complexity being generated by simple specification; of precise equations having unpredictable consequences. That there are these possibilities is very surprising to those of us who were brought up on the study of those "tame," predictable mathematical systems on which we cut our mathematical teeth and which provided the standard teaching examples for generations of students. The recognition of structured chaos has been hailed as a third revolution, worthy to be set alongside the Newtonian and quantum mechanical revolutions that preceded it.[3]

The resulting worldview is certainly not that of a dull mechanical regularity. Indeed, the behavior envisaged has more than a touch of the organismic about it. This feeling is reinforced by consideration of other insights into physical process that have been gained in recent years. I am thinking of the study of dissipative systems, whose behavior has been a major topic for investigation by Ilya Prigogine and his collaborators (Prigogine and Stengers 1984; see also Polkinghorne 1988, chap. 3). These systems are maintained far from equilibrium by an inflow of energy from the environment. The spontaneous triggering effects of small fluctuations, too tiny to be directly discernible, induce an order that is maintained by the flow of energy. The red spot of Jupiter, which has maintained its shape for centuries amidst the turbulent eddies of that planet's atmosphere, is thought to be an example. The order thus supported may be dynamically changing, as in the so-called chemical clock. With a carefully controlled steady inflow and outflow of materials, the chemical constituents in a mixture are found in certain circumstances to perform rhythmic oscillations from one concentration to another and back again, an astonishing effect involving the "collaboration" of trillions of molecules. In this kind of phenomenon one sees the generation of novel and large-scale order which seems quite incomprehensible at the microscopic molecular level. Physics is found to describe processes endowed not just with being but also with becoming.

The physical systems about which I have been talking are complicated, but they fall far short of the complexity of even the simplest living cell. Its biochemical dance also exhibits the combination of openness and order that we have encountered. In an as yet small and imperfect way, one might hope to begin to see some chance of gaining modest insight into how the levels of physics and biology might eventually be found to interlock in their description of the world. Prigogine and Stengers say of their account of these matters that "we can see ourselves as part of the universe we describe" (Prigogine and Stengers 1984, 300).

Wonderful! But is it all an illusion? How really open are chaotic systems? Certainly they are unpredictable, but that is because of the inexactitude of our knowledge of initial conditions, combined with these systems' exquisite sensitivity to the precise character of those conditions. Yet the examples we have considered are all, in fact, deterministic. Take equation (1) in the chaotic regime. If I really knew that I started with $x = 0.3$ (and not, say, 0.3000001), then all the subsequent x's would be explicitly calculable from the formula, however they might jig around. In other words, what we have encountered so far is no more than an epistemological limitation (our inability to know enough detail to determine what will happen) without its having any real ontological consequence (what is actually the case is still fully determined in its outcome). That is certainly so for equation (1). Is it also true for more complex and physically interesting systems, such as the earth's actual weather (rather than a simple model of it)?

As the mathematical physicist reads the situation "from below," what will often appear to be happening is mere unpredictability. Out of determinism has arisen apparently random behavior, but the underlying reality is still held to be purely mechanical. Our limited intellectual powers force us scientifically to think from bottom to top, from underlying simplicity to overall complexity, at least initially. Scientists need a manageable starting point for their discussions, either in terms of elementary constituents or in terms of a model of abstracted simplicity. We are not clever enough to start with complexity. A mathematician readily grasps the simple rule defining the Mandelbrot set and then comes upon that set's unlimited richness of structure with great surprise. No one, not even Mandelbrot himself, has the ability to start with the set, to grasp it *ab initio*. Analogously, when we talk about the structure of matter, we start with the simplicities of elementary particle physics rather than the complexities of the theory of condensed matter or of biology.

Our thought is constrained to a one-way reading of the story, in which the higher emerges from the lower. In consequence, the latter retains its hold upon our mind as controlling the metaphysical picture. It is by no means clear that this is more than a trick of intellectual perspective. In other words, the characteristics of the elementary level (whether deterministic, or quantum mechanical, or whatever) may be as much emergent properties (in the direction of increasing simplicity) as are life or consciousness (in the direction of increasing complexity). Subatomic particles are not only not "more real" than a bacterial cell, they also have no greater privileged share in determining the nature of reality. That structured chaos can arise from deterministic equations is a mathematical fact. That fact by itself does not settle the metaphysical question of whether the future is determined or, on the contrary, the world is open in its process.

It might, perhaps, be suggested that quantum theory has already settled that issue for us. The most widely held interpretation of that theory's meaning regards individual quantum events as being radically random, so that when the wave function "collapses" onto one of the possible results of a macroscopic observation, the process of the physical world has taken a turn in a particular and intrinsically novel direction (see Herbert 1985, chap. 8; Polkinghorne 1984, chap. 6). Something unforeseeable has come about. The apparent regularity of so much macroscopic experience is held simply to be the statistical effect of the law of large numbers, the essentially predictable average of many stochastic events. One might then go on to suppose that in the case of macroscopic systems in regimes of chaotic behavior, their exquisite sensitivity to detailed circumstance would effectively enmesh them in a microscopic world of quantum uncertainty. (In attempting prediction one would soon reach levels of required accuracy denied to us by Heisenberg's uncertainty principle.) Thus the openness of physical process would seem to have been established, even from a bottom-up point of view. In fact, the matter is more complicated than that, for three reasons.

The first complication relates to the character of quantum physics. If one takes a foundational view of the role of elementary particles, then the Schrödinger equation is the true equation, rather than any of those proposed by classical physics. At the time of this writing there is a hot debate about whether this equation generates chaotic behavior. It is certainly known that the analogues of some systems that are classically chaotic (for example, the so-called kicked rotator) are not chaotic quantum mechanically. Intuitively, one might conjecture that this had something to do with quantum fuzziness on length scales of the Compton wavelength and less, which would not permit the infinitely repeating fractal behavior that seems to be associated with true chaos.[4] It is not known how typical are these quantum systems that have been studied and found not to be chaotic. Perhaps quantum mechanics requires a characterization of chaotic behavior different from descriptions so far advanced. It would be extremely perplexing if chaos were totally absent from the quantum world, especially in the limit as Planck's constant becomes small, where correspondence-principle arguments encourage the expectation of recovering classically describable behavior. Joseph Ford has commented that "should chaos not be found in quantum mechanics, then an earthquake in the foundations of physics appears inevitable, say about magnitude twenty on the Richter scale" (Davies 1989, 366).[5]

A second reason for caution is that the whole question of the nature of quantum reality is still a highly contentious issue. Our discussion so far has been in terms of the mainstream understanding held by most physicists (which I share). There are, however, radically different proposals that also have their supporters. David Bohm's deterministic version is as empirically adequate as the conventional account, even if it appears to many to be unpersuasively contrived. The many-worlds interpretation holds that everything that can happen, does happen, even if that implies many alternative yet realized histories for the universe. I am not at all convinced by either of these options, but they remain on the metaphysical table, and so they put question marks against any simple claim that quantum theory by itself establishes the openness of physical process.

A third complication relates to an unresolved problem in the interpretation of quantum theory. How does a fitful theory yield a definite observational answer each time it is investigated experimentally? The measurement problem in quantum theory has received no agreed solution, but among the possibilities being canvassed is one that would see quantum theory itself as a downward-emergent approximation to a more complex physical reality. The matter is somewhat technical, and certainly contentious, so I have relegated its discussion to a note at the end of this article.

These considerations lead one to be cautious about invoking quantum theory to establish the openness of physical systems. We are encouraged to go on to inquire about the possibility of augmenting bottom-up thinking by intellectual traffic in the opposite direction. Accordingly, I return to the question of whether some of the characteristics discerned in low-level exploration of the world (basic physics) may not be regarded as emergent at that level, so that they need not be made universally prescriptive for metaphysics. To address the issue bluntly: If apparently open behavior is associated with underlying apparently deterministic equations, which is to be taken to have the greater ontological seriousness—the behavior or the equations? Which is the approximation and which is the reality? It is conceivable that apparent determinism emerges at some lower levels without its being a characteristic of reality overall. For instance, it might arise from the approximation of treating subsystems as if they were isolatable from the whole, which in fact they are not, as subsequent discussion will show (p. 935). But first let us consider a philosophical argument.

I take a critically realist view of our scientific exploration of the world. Such a position implies the possibility of gaining verisimilitudinous knowledge, which is reliable without claiming to be exhaustive. In that case, what we know and what is the case are believed to be closely allied; epistemology and ontology are intimately connected. One can see how natural this view is for a scientist by considering the early history of quantum theory. Heisenberg's famous discussion of thought experiments, such as the gamma-ray microscope, dealt with what can be measured. It was an epistemological analysis. Yet for the majority of physicists it led to ontological conclusions. They interpret the uncertainty principle as not being merely a principle of ignorance (as Bohm, for example, would interpret it) but as a principle of genuine indeterminacy. In an analogous way, it seems to me to be a coherent possibility to interpret the undoubted unpredictability of so much of physical process as indicating that process to be ontologically open.

The option is there, but it is not, of course, a forced move to choose it. The case for doing so is greatly enhanced if one acknowledges the necessity of describing a physical world of which we can see ourselves as inhabitants. There are, of course, metaphysical traditions that deny that necessity. Cartesian dualism draws a sharp distinction between a realm of pure extension, in which even animals are only automatons, and the human realm of minds-in-bodies. I have elsewhere (Polkinghorne 1988, chap. 5) given reasons for rejecting that picture and attempting to replace it with a complementary mind/matter metaphysic which sees the world-stuff as being, in an emergent-downward mode, the matter of which physics speaks and, in an emergent-upward mode, the mind that we experience (the direction being that of increasing complexity and flexibility of organization). There is some relation here with the thought of Jürgen Moltmann, innocent as it is of any detailed concern for scientific insight. In his discussion of what it can mean to say in the Creed that God is the Creator of "heaven and earth," Moltmann decides that creation is an open system, and "We call the determined side of this system 'earth,' the undetermined side 'heaven'" (Moltmann 1985, 163). One might say that "earth" is process read downward toward determinism, and "heaven" is process read upward toward participation in spiritual reality.

There are also metaphysical traditions which deny that the incorporation of humanity into their scheme requires any relaxation of a deterministic picture; hence the age-old philosophical debate concerning free will and determinism. (This is not the place in which to attempt a detailed discussion of these issues.) Donald MacKay was prepared to argue that even if one conceded the world to be deterministic (a concession he did not necessarily endorse but that might have been more congenial to his Calvinist theology, with its rigid notion of God's sovereignty, than would be the case with my theological thinking), nevertheless, there would still be a logical independence of the personal I-story in relation to the scientific O-story (see MacKay 1988, esp. chaps. 5 and 6). Such independence would allow a kind of squaring of the circle in permitting both a determinist account (O) and an open account (I) of reality. I do not believe that this approach succeeds. I do believe that, in the end, the denial of human freedom is incoherent, because it destroys rationality. On its own terms, its very utterance, though purporting to be reasoned, is no more than the mouthing of an automaton. Like all extreme critiques born of the hermeneutics of suspicion, it ultimately proves to be suicidal.

A consequence of the delicate sensitivity of complex dynamical systems to circumstance is that they are not only unpredictable but also intrinsically unisolatable. A favorite example to illustrate this is collisions of gas molecules, treated as if they were tiny classical billiard balls. (Of course they are not, but the model is a good one for many purposes.) So rapidly do the effects of initial circumstances exponentiate in a sequence of collisions that, at normal temperature and pressure, the fifty or so collisions that take place for each molecule in the space of only 10^{-10} seconds would differ significantly in their outcome if an unconsidered electron (the smallest particle of matter) were on the other side of the observable universe (the farthest distance away) interacting through its gravitational attraction (the weakest of the fundamental forces of nature). Even so simple a system as air, in a period as short as less than a millimicrosecond, would require universal knowledge for its adequate fine-grained discussion. Again, we are given cause for caution in accepting that a bottom-up, intrinsically atomistic description of nature is a sufficient basis for metaphysics. The notion of a set of isolated basic entities is a highly abstracted idea. As an elementary-particle physicist, I do not question the utility of the notion for some purposes, only its adequacy for all.

That message is reinforced by further consideration of the quantum world itself. I now look to aspects of the subject that are not matters of disputed interpretation, like some of those considered earlier. Whatever one's views on those issues, the theoretical analyses of John Bell and the experimental investigations of Alain Aspect and his collaborators have made it clear that an inescapable nonlocality is involved in the phenomena (see, e.g., Polkinghorne 1984, chap. 7). Quantum entities exhibit a counterintuitive togetherness-in-separation—a power, once they have interacted, to influence each other however far they subsequently separate. Paradoxically, the atomic world is one that cannot be described atomistically. A very careful and lucid discussion of the issues that this raises has been given by Bernard d'Espagnat (1989), who is emphatic that philosophy must take account of what physics has to tell it. "We may imagine that to reach the truth we only need to come up with brilliant ideas," but that is mistaken, for "it remains illusory to hope that in our day people can still make valid claims on matters such as reality, time and causality, if these claims are not rooted in the extraordinarily elaborate factual knowledge now at our disposal" (d'Espagnat 1989, 16). d'Espagnat is a realist, for he feels that denial of an independent reality leads to the danger of collapse into solipsism, a person being driven to retreat into the sole refuge of his own thinking mind. Yet quantum theory denies the possibility of embracing a naive and particulate objectivity in our account of the physical world. d'Espagnat summarizes the dilemma: "It was once thought [e.g., by positivism] that the notion of being must be repudiated. Now that it has finally become apparent that to do so is to court incoherence, it is dismaying to find that in the interim it has become peculiarly difficult, if facts are to be respected, to rehabilitate that notion" (d'Espagnat 1989, 11).

D'Espagnat's solution is to speak of independent reality as "veiled" and to be distinguished from empirical reality. That sounds at first like a proposal to move in a Kantian direction of discriminating between phenomena (things as they appear) and noumena (things in themselves), but d'Espagnat does not go all the way with Kant. He insists that independent reality is veiled rather than inaccessible; it is elusive rather than absolutely unknowable. He wishes (as I do too) to give all due weight to the insights of physics, but he also acknowledges that "it does not seem incoherent to me to admit the possibility of rational activity that does not issue in 'demonstrative certainty' in the sense we scientists use the expression" (d'Espagnat 1989, 210). Because I feel very strongly that this is so, I am driven to greater metaphysical boldness than d'Espagnat will permit himself. Nevertheless, I believe that his cautious invocation of veiledness is, at the least, not inconsistent with the kind of openness about the nature of reality that I am trying to explore.

The picture that has been building up is that of a physical world liberated from the thrall of the merely mechanical but retaining those orderly elements that science has been so successful in exhibiting and understanding. In Popper's famous metaphor, it is a world of clouds and clocks, in which some things are indeed predictable but others are open to the possibility of new development. I have elsewhere argued that such a world of intertwined order and novelty is just that which might be expected as the creation of a God both faithful and loving, who will endow God's world with the twin gifts of reliability and freedom (Polkinghorne 1988, chap. 4).

In a bottom-up description of the physical world, the onset of flexible openness is signaled by the myriad possibilities of future development which present themselves to a complex dynamical system. In a quasi-determinist account they arise from the greatly differing trajectories that would result from initial conditions differing only infinitesimally from each other. Because of their undifferentiable proximity of circumstance, there is no energetic discrimination between these possibilities. The "choice" of path actually followed corresponds, not to the result of some physically causal act (in the sense of an energy input), but rather to a "selection" from options (in the sense of an information input). One might well be able to formalize the last point. Typically, the open options can be expressed in terms of bifurcating possibilities (this or that), whose particular realizations resemble bits of information (switches on or off, in a crude computer analogy). In a top-down description of systems of such complexity as ourselves, this "information input" is a picture of how mind could operate causally within a complementary mind/matter metaphysic. Because flexibility only arises within intrinsically unpredictable circumstances, the springs of the operation of mind would be inescapably hidden ("veiled"). The search for a modern equivalent of the Cartesian pineal gland would be the search for a will-o'-the-wisp; it is condemned to failure.

It is by no means clear that information input of the kind described originates solely from animals, humankind, and whatever similar agents there might be. I do not believe that God is contained within the mind/matter confines of the world (Polkinghorne 1988, 79-82), but it is entirely conceivable that God might interact with it (both in relation to humanity and in relation to all other open process) in the form of information input. I have attempted elsewhere to explore some of the theological consequences of such a view, particularly in relation to questions of prayer and theodicy (Polkinghorne 1989). God is not pictured as an interfering agent among other agencies. (That would correspond to energy input.) Instead, form is given to the possibility that God influences God's own creation in a non-energetic way. Many theological writers have recoiled from the detachment of deism and have wished to assert an interactive relationship between God and the world. They have been notably coy, however, about how this might actually come about. Austin Farrer's account of double agency is so emphatic about the inscrutability of the divine side of it as to provide us with no help (see Polkinghorne 1989, 11–13). The various varieties of panentheism (asserting the world to be part, but not the whole, of God) afford no more than an image of divine action—and an unsatisfactory one at that, in my opinion (Polkinghorne 1989, chap. 2). Arthur Peacocke has offered us the picture of God as "an Improviser of unsurpassed ingenuity" (Peacocke 1986, 98), seeking to incorporate the discords of evil into a greater harmony, but how that Great Improviser actually touches the keyboard is not made clear. The idea of divine interaction through information input seems to me to afford us some help in the matter.[6]

The view I am proposing has been criticized by some reviewers of its earlier articulation as a return to the discredited notion of a "God of the gaps." I disagree. One must be careful not to be carried away by verbal analogies more apparent than real. If there is any free action (human or divine), it seems to me that there will have to be "gaps" or opennesses in physical process, as it is described from the bottom up. The correct lower-level description can only provide an envelope of possibility within which top-down causation will find its scope for realization. We are "people of the gaps" in this sense, and it is surely not an error for God's interaction to be thought of in an analogous way, for the gaps to which we are now referring are intrinsic. They contrast with the arbitrary gaps of the old-style argument, which were simply patches of current ignorance, with no enduring status attached to them. Of course, the ideas I am presenting here are speculative, but we have to be bold enough to make some venture in the matter. Otherwise, talk of top-down causation (however phrased) is no more than the utterance of slogans whose conceivable validity is completely unclear.

The picture being suggested here of the mode of God's interaction with God's creation, over and above the same God's great act of sustaining it in being, might seem to bear some cousinly relation to the notions of process theology, which built upon the metaphysical scheme elaborated by A. N. Whitehead (see Cobb and Griffin 1976). The latter takes as its fundamental entities "events," and each event has a dual character, possessing a kind of psychic pole (prehension) in which a "choice" of possibilities is made, followed by a material pole (concrescence) in which the selected option is realized. In process theology, God's action is in the form of a lure, a continuing attempt to entice the world in a certain direction, although, in Whitehead's view, all true initiative lies with the world itself in acts of concrescence. He reacted violently against the classical picture of God as a "cosmic tyrant" in tight control of all that happens, but to many he has seemed to end with what Eric Mascall wittingly called the picture of a God more to be pitied than worshiped, as the Deity stands pleading from the sidelines of the world.

I do not think that Whitehead's episodic scheme of a concatenation of events (so that entities are secondary constructs made out of strings of events) is at all persuasive. Though it might bear some superficial resemblance to the occasional fitfulness found in quantum measurement, it fails to accommodate such a concept as that of a quantum field, whose essence is the combination of quantum discreteness with the continuity characteristic of a field. Nor do I find the implicit panpsychism involved in talk of prehension to be at all congenial or convincing.

The metaphysical scheme espoused in this essay succeeds, in my opinion, in retaining some of the attractive features of process thought without its defects. It is a kind of demythologization of that panpsychic worldview. God is certainly not a cosmic tyrant; and God's interaction with God's own world can be expected to respect its freedom (including our own).[7] God's acts will be veiled within the unpredictability of complex process. They may be discernible by faith, but they will not be demonstrable by experiment. God is not condemned to the sole role of passive pleader—the fate assigned in process thought; on the contrary, God is able to act. The flexibility in what happens is not assigned to the operation of a mysterious psychic pole in each material event. Instead, it arises naturally from what we have been able to discern scientifically about the nature of physical process. I do not claim that age-old problems are solved, but simply that there is a hopeful way in which we can look at them, while retaining the integrity of our experience and understanding in all their aspects: scientific, personal, religious.

A Note on Quantum Measurement

An unresolved problem in the interpretation of quantum theory relates to the act of measurement (see Herbert 1985, chap. 8, and Polkinghorne 1984, chap. 6). The theory only predicts the probabilities for a variety of possible outcomes of an act of observation performed on a quantum mechanical system. How does it come about that, when any such measurement is made, a definite and particular answer is obtained? How does the fitful quantum world interlock with the reliable world of laboratory apparatus to give a specific result?

A variety of proposals, none wholly satisfactory, has been made. The most popular (a form of it was endorsed by Niels Bohr as the received Copenhagen interpretation) assigns the defining role to the intervention of large-scale classical measuring apparatus. The difficulty with this view is that such measuring apparatus is itself made of quantum constituents. How does this determining property of "collapsing the wave function" (to use the technical phrase) "emerge" from its indeterminate quantum substrate? The question has not been answered. Posed in this way, it is framed in the spirit of bottom-up thinking, which treats the quantum mechanical as given and the role of the measuring apparatus as the thing to be explained.

A different approach has been suggested by some other physicists (notably Eugene Wigner). Mathematical analysis indicates that the determining role must be played by a system possessing the property of nonlinearity in order to break the linear superposition of a variety of outcomes, which is the formal expression of quantum theory's undecidedness. The proposal has not gained wide support, though Roger Penrose has recently argued in favor of such an approach (Penrose 1989, 296–99). If it were to prove correct, it would be an example of downward emergence. The true equations of physics are held to be nonlinear, but in a way that is only significant for large (classical) systems. Conventional quantum theory, and its linearity, would then be an emergent property of small systems.

NOTES

1. The variable x is the actual population divided by the maximum possible value.
2. This discovery of universal behavior introduced a new natural constant into mathematics, the Feigenbaum number, 4.669 . . .
3. One important feature of the new dynamics is that its equations are usually nonlinear.
4. One might have guessed that it was due to the linearity of the Schrödinger equation, but this does not seem to be the case; see Davies 1989, 369.
5. J. Ford's article (in Davies 1989) contains a good account of the problem of quantum chaos.
6. There are connections here with Bowker's notion of religions as systems; see Bowker 1987, 112–43.
7. There are obvious connections with the dialectical theism of Macquarrie (1984).

REFERENCES

Bowker, J. 1987. *Licensed Insanities: Religions and Belief in God in the Contemporary World.* London: Darton, Longman, and Todd.
Cobb, J. R., and D. R. Griffin. 1976. *Process Theology: An Introductory Exhibition.* Philadelphia: Westminster Press.
Davies, P. W., ed. 1989. *The New Physics.* Cambridge: Cambridge Univ. Press.
d'Espagnat, B. 1989. *Reality and the Physicist.* Cambridge: Cambridge Univ. Press.
Gleick, J. 1988. *Chaos.* London: Heinemann.
Herbert, N. 1985. *Quantum Reality.* London: Rider.
MacKay, Donald. 1988. *The Open Mind and Other Essays.* Leicester, England: InterVarsity Press.
Macquarrie, J. 1984. *In Search of Deity.* London: SCM Press.
Moltmann, J. 1985. *God in Creation.* London: SCM Press.
Peacocke, A. R. 1979. *Creation and the World of Science.* Oxford: Oxford Univ. Press.
———. 1986. *God and the New Biology.* London: Dent.
Peitgren, H.-O., and P. H. Richter. 1986. *The Beauty of Fractals.* London: Springer.
Penrose, R. 1989. *The Emperor's New Mind.* Oxford: Oxford Univ. Press.
Polkinghorne, J. C. 1984. *The Quantum World.* London: Longman.
———. 1986. *One World.* London: SPCK.
———. 1988. *Science and Creation.* London: SPCK.
———. 1989. *Science and Providence.* London: SPCK.
Prigogine, I., and I. Stengers. 1984. *Order Out of Chaos.* London: Heinemann.
Stewart, I. 1989. *Does God Play Dice?* Oxford: Blackwell.
Weinberg, S. 1977. *The First Three Minutes.* London: Andre Deutsch.