THE EMERGENT ORDER

by Kevin Sharpe and Jonathan Walgate

Abstract. We examine the phenomenon of emergence, referring particularly to Arthur Peacocke's ideas on emergence, the self, and spirituality. He believes that the whole of an emergent structure influences the way its parts cohere and that emergent structures (including minds and persons) and their effects are very important. He thereby hopes to remove the reductionist challenge that seeks to understand a whole fully in terms of its parts. We argue that emergent phenomena are not influential in the above sense. The holistic completeness of these structures at their own theoretical level does not substitute for the causal independence Peacocke suggests by the idea of influence. Some computer simulations that generate emergent complexity follow simple and self-contained sets of rules. Peacocke also adheres to a hierarchical account of reality as a series of levels into which matter is organized, running from atoms through molecules to cells and eventually to whole ecosystems. But influential behavior does not respect this ordering. Further, Peacocke's opposition to reductionism is unnecessary; any "completeness" of lower-level models does not imply the redundancy of higher-level descriptions. Emergence transforms reductionism into a constructive and positive principle.

Keywords: chaos; divine-universe interaction; downward influence; emergence; hierarchies of levels; holism; Nancey Murphy; Arthur Peacocke; reductionism; scientific models; self-organizing criticality; supervenience; whole-part influence.

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[*Zygon*, vol. 38, no. 2 (June 2003).]

Emergence is a newcomer to the dialogue between science and spiritual thought, but it already demands serious consideration. Though the subject may seem unfamiliar, the subject matter is not. Examples of emergent structures abound. The rings of Saturn, for instance. Or the coherent biochemical constructs that we call our cells and that act as unitary building blocks for a "higher" and emergent biological order. Perhaps even our selves are emergent structures.

A proper appreciation of emergence can enhance our understanding of many disciplines, from elementary physics to biology to spiritual thought. This essay develops the path that Arthur Peacocke follows. He, perhaps more than any other, highlights the spiritual significance of these scientific discoveries.

Productive new ideas encourage debate. Mathematicians, physicists, biologists, and spiritual thinkers acknowledge the phenomenon of emergence—and draw their own conclusions from it. They differ markedly because the phenomenon is ill understood. Progress in the debate occurs because, as we learn more about emergence, we learn more about its impact on our metaphysics.

Two key areas for spiritual thinkers involve the impact of emergence on reductionism and the potential of emergence to describe the Divine's interaction with the universe. The two intertwine because how spiritual thinkers approach the latter question often relies on emergence to counter reductionism. Further, the arguments are metaphysical and involve semantic nuances. What does it mean for something to be real? What is causal influence? For that matter, what is it about reductionism that spiritual thought finds it hostile? The real universe may help resolve some of these issues. Spiritual argument has so far revolved principally around the datum that emergence exists but has paid little attention to how emergence arises. Increasingly, we can now study the nature of emergence. This provides clues that will color our metaphysical semantics.

HIERARCHIES

Many objects in the universe comprise other objects. Production lines assemble cars from raw parts like engines and wheels, and these in turn are made of valves, pistons, nuts, and bolts. This says little about the nature of reality, because parts like nuts and bolts behave in the same kind of way that cars do. The same Newtonian laws about force and acceleration apply to both. New concepts do arise at the "level" of the car—driving, steering, reversing, and so on—but these relate in an understood way to the more basic physics of the parts. We know how to build cars and their parts because of this relationship.

If we could construct and deconstruct all the universe and everything in it as easily as we can a car, we could understand everything as built from simple parts using the parts' rules. Reductionism would be true. But things do not follow such a simple course. We know that living matter comprises things called cells, for example. We know how to grow cells, and we are learning how to manipulate them in more and more refined ways. We know a great deal about them, and we call that "great deal" biology. But we do not know how to build a cell from scratch. Biology, in this sense, comprises a new level of knowledge, not built from more basic ideas but adduced directly from nature. We can, in this sense, speak of biology as "emergent."

Some scholars place scientific theories in a hierarchy of such levels, beginning with physics at the bottom and rising up through chemistry to biology and beyond. Nancey Murphy (Murphy and Ellis 1996, 19) describes it thus:

> It has long been recognized that the universe can be understood as a hierarchy of systems, organized according to level of complexity, from the inorganic, to the organic, the conscious, and the social. Thus, the natural and human sciences can be ordered hierarchically as well, according to the levels of complexity they study. The lower parts, at least, of the hierarchy can be ordered unambiguously:
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> Psychology
> Botany/Zoology/Physiology
> Biochemistry
> Chemistry
> Physics

Later in her considerations, Murphy advances a revised and "completed" hierarchy (1996, 86):

Ethics
Cosmology — Motivational Studies
Astrophysics — Social Sciences
Ecology, Geology — Psychology
Biology
Chemistry
Physics

Ladders like these are central to Murphy's and to Peacocke's understandings of emergence. Murphy portrays her ladder of the sciences as carved into the bedrock of reality. Peacocke more cautiously and rightly recognizes the importance of *proving* the irreducibility of one level to another. This means for him that a lower-level theory cannot in practical terms express the concepts of a higher-level theory (no sequence of firing neurons can adequately express "good intentions" in ethics). However, this is the observation that helps him draw the ladder in the first place. The observation only points to the incompleteness of lower-level scientific descriptions of the universe. It does not prove that we can ascribe an independent ontological foundation for higher-level theories, nor does it suggest the incompleteness of lower-level scientific models. Little attention has been draw to this distinction. Peacocke employs two terms, "top-down causation" and "whole-part constraint," to describe emergent behavior, apparently unaware of this difference. Investigating the physical facts of emergence—as we attempt in this essay—may help avoid such confusions.

The laws of nature do not form as neat a table as the hierarchy of sciences suggests. We need care, and we need clarity about what we observe and what conclusions we draw from our observations. Murphy suggests that, since we can *understand* the universe hierarchically, our sciences must form hierarchies. This may not follow, however. We do not know that the universe is organized hierarchically. (Nor do we yet know whether the totality of the universe can be understood hierarchically; after all, for all our successes, we understand little about it.) We only know that the sciences form hierarchic patterns. We suspect that this pattern correlates to something real.

The logic of the hierarchy can lead us to assume that the universe operates only this way. But it does not, and counterexamples abound both in the organization of the sciences and in the workings of the real universe. Take the organization of the sciences. On Murphy's chart, cosmology sits almost as distant a relative of physics as possible—so we might expect their subject matters to be unrelated. Not so. Cosmology forms a branch of physics. Particle physicists take a keen interest in cosmologists' work, and no cosmologist lacks a grasp of fundamental physics. Ecology presents a similar picture. Its units of species and ecosystems arise from biology below it. The modern ecological concern about the greenhouse effect, however, mixes scientific understandings of the scattering of radiation (physics), thermodynamics (more physics), and atmospheric gas chemistry. Other counterexamples to the universe's operating only hierarchically involve how the real universe works. Consider sight. A nuclear fusion reaction emits photons, which collide with photoreceptive cells, which generate electrical impulses in nerves, which carry to a network of neurons in the brain, which, at the end of the line, create an image in our mind. Meanwhile, more malign forms of radiation can damage cells in our bodies and lead to sickness. Biology and physics intertwine here, along with neurophysiology. Processes and events do not fit into neat hierarchical pigeonholes.

These examples do not prove that biologists think about the same things as chemists do. They only show that the hierarchy of sciences is more complex than it looks. Peacocke similarly cautions those encountering his list of levels of biological organization: "for convenience only and with no other implications," he writes, "we often call each member of this series 'higher' than the one preceding it in this list" (Peacocke 1979, 113). He does not think that the higher sciences are "better" than the lower ones, or vice versa; he merely wants to point to the observed hierarchy of complexity (that cells are made of molecules, that molecules are made of atoms, and so on). We would suggest, however, that those who use this terminology want to say something stronger than merely pointing to an observation. Observation involves interpretation. The list asserts an ordered relationship between the sciences, but what is this relationship and why does it hold? If we reverse the ordering of the list, it would assert something quite different. Why should it run one way and not the other? The word *emergent* inspires the question, From what? To find out about emergence and the ideas it generates, we need to know *how* emergence brings about the hierarchy. The hierarchy is not a given; we do not need the information on emergence in order to proceed directly to conclusions about reality; the idea of hierarchy is not the beginning of the theory of emergence. It is a product of theory.

We now can return to our original questions. We want to look at reductionism and emergence. Can we justify the value of the higher sciences on the basis of the emergent behavior that this hierarchy suggests (but does not define)? Can we draw stronger conclusions about the nature of reality? Do emergent theories reflect holistic operations that counter the reductionist thesis? Peacocke answers these questions in the affirmative and goes on to use emergence as a metaphor for divine interaction with the universe. The first question does demand a "yes." The second and third require further thought.

SEMANTICS

Reality. Given reductionism and emergence, what can we say about the nature of reality? The archreductionist rejects the reality of the objects of familiar experience and the concepts of the higher sciences. They are illusory patterns, the reductionist contends, that quarks and leptons form. Only these fundamental particles are really there. The rest is a type of mirage that the microscopic creates.

This philosophical position is old. The game of reductionism, Peacocke writes, "has been played ever since the days when Democritus and Lucretius, by their atomistic determinism, tried to reduce the whole of human life and the history of the universe to a mere concatenation of colliding atoms—with obvious implications for the concepts of human mental processes and autonomy" (1979, 113). Peacocke characterizes modern proponents of these arguments: "Our colleagues coming from another discipline, claim that our discipline X is 'nothing but' an example and application of discipline Y." Such attempted reductions are commonplace in all disciplines; religion to sociology, for example, or biology to chemistry and physics. "The prizes," says Peacocke, "are a sense of superiority . . . and the malicious joy at watching the apoplectic response of one's colleagues as one devastatingly demonstrates their discipline is not only a waste of time but unworthy of the receipt of grants from limited funds" (1979, 112).

Peacocke writings can lead to several points about extreme forms of reductionism:

- If pre-twentieth-century science only studied illusions, then modern particle physics may also only study illusions because some day we may discover that quarks comprise even simpler building blocks.
- Extreme reductionisms can descend into absurdity: if they deny that my mind and its mental processes are meaningfully real, then the ideas and arguments of hard-line reductionists are nonexistent and irrelevant to the nature of reality.
- We can recover the common sense of the word *real* from reductionism. Without fear of later contradiction and if all our knowledge comprises mirages, we can redefine such illusions as the fabric of reality.

We gain nothing by devaluing our idea of reality so that it cannot encompass our everyday experience. It produces no scientific benefit and no philosophical clarity.

We also reject the alternative extreme, the denial of any reductionism. Vitalism maintains that entities and processes not present in inorganic matter pervade bodies apparently constructed from smaller parts, in particular the cells and organelles of living beings. These mysterious forces—the élan vital of Henri Bergson—supposedly create the reality of life. Though vitalist ideas may have possessed some currency before this, they were discredited with the union of inorganic and organic chemistry and Friedrich Wöhler's 1828 synthesis of urea, one of the simplest organic compounds, from inorganic raw materials.

A restrictive picture of ontology produces the two mistakes of extreme or no reductionism. When we say something is real, we admit it plays a role in our ontology. But when we say two different things are real, we do not mean they play the same role in our ontology. Nor do we mean they are independent of one another in it. This mistaken impression holds over from the old atomist philosophy, which saw the universe as a collection of atoms colliding and recoiling, and whose ontology comprised a list, a register of particles present. Current philosophy imagines reality structured in tune with observations and experiences, and we experience a great deal of pattern, order, and structure in the universe. A billion ontological registers could not do this justice. Our ontologies must be active, filled with structure and process. Our ontologies must give equal reality to the patterns and structures we can describe, characterize, and observe on many levels. (The patterns and structures need not be equally widespread, or equally valuable for explanation, or equally pronounced. But they are all equally there.)

We must walk a middle path between the extremes of total or no reductionism. Objects composed of simpler parts must have ontological significance. They must really exist, not because of any property they inherently possess but because of what we mean by the word *existence*. We need not make this point philosophically or appeal to emergence. Nor need any additional substance provide their reality. The universe just seems built this way.

Theory. Chemists and biologists study aspects of reality as much as do physicists. This moves the debate surrounding reductionism to a subtler level where emergence becomes relevant. Good theories about how the universe works reflect patterns that exist in reality. This marks the belief behind critical realism that we can, through empirical study, arrive at good theories. We have no satisfactory reason to doubt this hypothesis and many satisfactory reasons to affirm it; we may therefore assume that our theories describe reality. Trustworthy theories therefore suggest that the ideas and concepts filling them correspond to real objects and forces. No physicist would doubt the existence of electrons. Though we will never see electrons except via their influence on other devices, our descriptions of reality involve them so much that we expect them to exist.

We can sometimes do without some basic concepts in science. We could, for instance, describe the lattice structure of a crystal without talk of atoms and treat everything in terms of shells of electrons that orbit nuclei. The two descriptions amount to the same thing, and, though removing the idea of an atom labors our description, it is just as accurate. This does not mean that atoms do not exist. It might mean, though, that they are less fundamental to our theories than are electrons. When the "Almighty" wrote the "rule-book" of the universe—setting out exactly how nature behaves—"He" need not mention atoms by name. "He" need only outline the behavior of electrons and quarks, and thereby imply the physical possibilities of atoms without explicitly stating them. However, we currently must include electrons and quarks, some of the smallest building blocks known to physics, in our theories.

Emergence suggests that we must also include other basic ideas, some of which lie at more complex scales than that of electrons and quarks. We cannot describe cells in terms of molecules, or organs in terms of cells, or ideas in terms of neurons. Atomist reductionism is inaccurate as an all-encompassing explanation. Wholes (complex objects composed of parts) inevitably occur in scientific descriptions of the universe, occurrences not limited in scope. The state of a whole can describe the state of its parts. This justifies for Peacocke his talk of downward influence; he concludes that "an influence of the state of the system as a whole on the behavior of its component units—a constraint exercised by the whole on its parts—has to be recognized. . . . We may call this 'top-down' causation" (Peacocke

1993, 53). Later, he calls it top-down restraint, and later again, top-down influence; we shall label it "downward influence" (Peacocke 2000). He then provides the example of the Bernard phenomenon where a cell appears to "tell" its constituent molecules how to behave: "beyond the critical point, individual molecules in a hexagonal 'cell,' over a wide range in the fluid, move with a common component of velocity in a coordinated way, having previously manifested only entirely random motions with respect to each other" (Peacocke 1993, 53).

Collections of objects of course behave differently when in different arrangements. Electrons behave differently as part of an atom than when not. If we knew that a certain object were an atom, we would know that the electrons inside it follow orbital trajectories just as the molecules in a Bernard cell display regimentality. Yet, Peacocke writes of the molecules in Bernard phenomena being "made to behave otherwise than they would in isolation" (1993, 54). His point is not only that the molecules behave differently when they form a cellular pattern than when otherwise. He also concludes that downward influence occurs here. Something from outside the molecules makes them behave regimentally. Need he conclude this? We do not conclude that atoms display downward influence on their electrons any more than we imagine that the solar system exerts downward influence on the planets to arrange them in orbits. We know that gravity, not some holistic influence, best explains planetary orbits. We know that electromagnetic attraction between the electrons and the proton-filled nucleus, not some holistic influence, best explains atomic structure. So why does Peacocke invoke downward influence in the Bernard phenomenon and other emergent structures to explain their emergent properties?

Do his points prove his claim that emergent objects are fundamental to our theories in understanding reality, as are atoms versus quarks?

Influence. Peacocke posits downward influence because we do not have a neat explanation of Bernard-like behavior as we do for orbital behavior. He thereby suggests that no neat, reductionist explanation of Bernard-like behavior exists. If Peacocke's assumption is right, the simplest and most elegant (and therefore best) way to understand the phenomenon requires the whole-part influence he outlines. Further, because we uphold critical realism and the validity of scientific method to discover facts, we must accept that the simplest explanation for a state of affairs represents reality. If we cannot best explain the coherent action of the parts in emergent phenomena—whether muscle cells in the heart or molecules in a Bernard cell—with the rules governing molecules or muscle cells, then our best explanation requires a real influence of the whole on its parts. This influence must be real. The universe therefore operates by both "standard" causation and by downward influence. This represents the end of one of science's most long-running metaphysical assumptions; downward influence is the antithesis of any reductionist program, not just extreme ones.

Advocates of this downward understanding differ over an important point. Murphy suggests, particularly in her account of human volition, that downward influence is on a par with the more common "bottom-up" causation. *As* gravity causes masses to attract, *so* Bernard cells cause their molecules to line up. *As* gravity causes masses to attract, *so* our minds cause our bodies to do what we intend. We should therefore not expect an explanation of emergent phenomena from more basic terms. "Basic terms" inadequately describe the universe, she thinks.

Peacocke offers a more correct analysis of downward influence. For him, downward influence occurs whenever downward terms best explain a phenomenon. This does not preclude some other, highly complex explanation in more basic terms. A downward explanation need neither defy nor limit the basic laws of physics. Rather, it "supervenes" on them.

A philosophical debate over the nature of supervenience and causation has arisen. Some scholars, such as Alexander Rosenberg, claim that supervenient properties are not physical. Others, like M. Weber, dispute this. Jaegwon Kim provides a widely quoted definition of supervenience, but the opposing sides of the debate both deploy it to support their claims. We can sidestep most of these arguments. Provided we know what we mean when we ask, Is there a simpler, more elegant explanation of emergent phenomena than downward influence? we can approach the question scientifically. We will know what we talk about when we know what we mean by "explanation."

Explanation. The ability of science to explain the workings of the universe poses a puzzle. Many scientists feel that the success of their enterprise, easily taken for granted, is not something we should expect. Why should a primate whose brain evolved to aid survival on the African savannah discover and understand quantum mechanics? The most remarkable thing about the universe, Albert Einstein's famous dictum says, is its comprehensibility.

That comprehensibility is mathematical. The success of the sciences lies in their pursuit of mathematically expressed explanations for what occurs in the universe. This holds for mechanics, with its explicitly mathematical construction, and the social sciences, with their reliance on correlation statistics. Mathematics resides everywhere in scientific explanation. When we ask what we mean by scientific explanations, we ask how we use mathematics to explain the universe. Our universe behaves mathematically.

We do not use mathematics to describe the universe. We use mathematics to model it. A description resembles a picture; it only displays what it displays and says what it says. A model, in contrast, resembles virtual reality; we can ask, What happens if we do this? and the model tells us. The solar system demonstrates this distinction. Newton's law of gravitation provides the basis for a scientific model of the forces acting on the planets. The Newtonian model inspired the scientific revolution because of its flexibility. We can ask, What if Earth were heavier? or What if Mars were given a sudden push? Newton's law has the potential to explain what occurs because we can model what would happen if things were different. We understand and explain how things are when we understand how they might be otherwise. Before Newton, Kepler geometrically described the motions of the heavens as ellipses. His description does not explain the motions of the heavens but only pictures them. If we ask what would happen if a comet hit Mars, the description can only respond with a protest: But a comet is not hitting Mars! We explain a phenomenon when we model it, not when we describe it.

Modeling something is usually more difficult than describing it, because modeling requires more knowledge about how things might be as well as how they are. When we turn to the "parts" of emergent phenomena, we often find them so complex and chaotic in their interlocking organization that we cannot, on practical grounds, describe their condition fully. Is modeling emergent phenomena impossible, then? Not necessarily; sometimes it is easier to build mathematical models of the universe than to describe it. Model builders have an advantage because they need only simulate the behavior of the real universe; they need not replicate it. Newton's model of the solar system, for example, pays no attention to the current positions of the planets. Just as well, because the nonlinear nature of his laws of motion renders the movement of the planets unpredictable in the long term. The impossibility of finding and listing the positions, orientations, and states of all the parts of emergent phenomena makes it impossible to describe them. But building a model does not require such lists. Model builders set general rules for how the parts should behave and then look at how they do behave. The trick lies in finding the right rules.

Emergent phenomena can confuse our understanding of downward influence. Emergent phenomena are so fundamental to our scientific descriptions of the universe that we cannot describe things built from them unless we refer to them explicitly. The simplest and most elegant description of an emergent phenomenon occurs at the level of it as a whole rather than at the level of its parts. We more easily and quickly understand our circulatory system if we teach that "the heart contracts rhythmically" rather than if we list the individual motions of all its cells. When we build a model of the circulatory system, however, we might first opt for a simple beating heart over a more complicated "electrically stimulated coagulation of muscle-tissue cells." We can, inside the simple picture, ask and answer questions like, What if the heart stopped beating? But we cannot model the heart at this level. "The heart contracts rhythmically" is really a description, not a model—there is no room for maneuvering, so there is no room for explanation.

The best way to describe an emergent system is to treat it as a whole. But the best explanation of a phenomenon does not lie at the same level as the best description; it lies at the level of the most elegant model. We must ask, Can we build simple, elegant models of emergent phenomena that do not explicitly refer to the phenomena themselves? If we can build such models, we can forget about downward influence. Its proponents ought to distinguish between scientific models and scientific descriptions.

Negative reductionism devalues knowledge based on levels of scientific description higher than the lowest available. A more important and positive reductionism holds that we can use our ideas about the parts of something to build the simplest, most elegant, and most general model of it. In turn, we can use our ideas of its parts to build the best model of it, and so on downward, with increasing elegance and generality. This constructive, not destructive, belief holds that the unitary stuff of reality constructs all the structures around us. More than methodological, this reductionism is ontological, a belief about the nature of reality. It thus conflicts with Peacocke's ideas of downward influence.

Playing Games

Simple rules can have consequences that are difficult to predict and sometimes surprising. Players of games know this. Anyone who has struggled to find the correct line of play in bridge or the strongest move in chess knows that the rules of the game tell only part of the story. Rules of thumb often offer the best guides to success: "Get your losers out early in no-trumps," or, "Never slow the tempo of your piece development." Why does this happen?

Chessworld. Consider Chessworld. In this imaginary universe, space consists of sixty-four squares, and the fundamental particles are the chess pieces: pawn, knight, bishop, rook, queen, and king. The fundamental laws explain the nature of the pieces and how they move. Some appear general: Pieces cannot move through each other. Pieces cannot occupy the same squares as each other. A piece cannot move to occupy the same square as another piece of the same color. A piece that moves to occupy the same square as a rival piece destroys it. One piece of each color moves alternately in sequence. A king may not be threatened with capture immediately after a piece of his color moves. Some laws of motion relate to specific pieces. For instance: Bishops move only diagonally. Kings move only one square, but in any direction. These laws combine to form the fundamental physics of Chessworld. Then, so long as we know the starting conditions of our chess universe, we can play.

A complete list of the laws of chess would fill no more than a few pages of text, yet more games of chess are possible than exist atoms in the universe. Our model of rules and pieces can simulate them all. Intelligent people have immersed themselves in this imaginary universe for lifetimes, but still the variations thrown up by our couple of pages of rules can surprise them. New and stronger lines of play still come to light twenty-five centuries after the game first appeared.

Some moves in chess lie beyond the Chessworld rules: A "fork" is a move where one piece simultaneously threatens the capture of two or more other pieces. A "pin" is a move that locks a piece in position because relocating it would expose the king to capture. "Castling" is a move where an as-yet-unmoved king shifts two squares rather than one and simultaneously pulls his rook around to his other side. Forking, pinning, and castling do not appear in the fundamental rules of Chessworld. Yet, every text will teach students to watch for them, and most junior players are aware of them. They can prove invaluable—forking and pinning for offense, and castling for defense.

These moves also teach us about reductionism and emergence. Structures and patterns exist in the real universe above the level of the physical laws. Cells, organs, and people exist. Does this rule out reductionism in the real universe? We can also ask this question of Chessworld. Structures and patterns—forks, pins, and castling, for instance—occur above the fundamental laws. We know the rules of chess and so can see if they predict all of what happens in a game, as in reductionism. We can as well see if some possible moves emerge beyond the rules.

Castling violates the basic laws of Chessworld; the king moves farther than he is normally allowed, and two pieces move through one another. An addendum to the preexisting laws of Chessworld, castling constitutes an exceptional rule that one may activate under specific conditions. It thus emerges beyond the basic rules. (Leading Spanish and Italian players devised castling in the fifteenth century to speed up play and appended it to the game.) To include castling in the standard format that records a game of chess requires the special symbols *0-0* and *0-0-0*. Complete accounts find the symbols indispensable. Further, chess computers must be explicitly programmed so that they can castle.

Forking and pinning also appear only in certain circumstances, and we can derive emergent rules about their behavior. But they differ from castling because the fundamental rules of chess explain what occurs in them. In a pin, for instance, the piece cannot move for fear of violating one of the most basic rules: we must not leave the king threatened. If we were unaware of the pin's explanation, we might understand it in terms of its large-scale structure downwardly influencing one of its parts. We would also continue to use pins. We just would not fully understand why they work.

Forking and pinning do not appear as special symbols in standard chess notation because the notation already allows for them. The fundamental rules of chess include them implicitly. Whenever they arise, we can trace a mechanism from the fundamental movements of the pieces that explains their existence and behavior. This does not denigrate their emergent existence or behavior. A chess champion does not look out for forks in the sense of "opportunities to create positions whereby two pieces of my opponent are five squares apart along one row, and I can place a knight between them on the adjacent row." Chess champions look out for forks. They also try to lock each other's pieces in position with pins. They interact and use these emergent though reducible phenomena as if they were perfectly real, because they *are* perfectly real.

Forking, pinning, and castling are not equivalent. While a piece's physics of movement implicitly includes its potential to fork or pin, a king's and rook's physics of movement does not include its potential to castle. Forking and pinning emerge from the fundamental laws. Castling does not emerge from anything. It reminds Chessworld's inhabitants of the imperfection and ad hoc approach of its designers. Forking and pinning better model and more closely resemble the emergent properties of the universe than does castling. They are emergent in the same sense that biological coherence emerges from the chemical laws that govern molecules.

Castling represents an antireductionist view of emergence. Many castling-type rules have been proposed for phenomena in our universe, but then better, more basic models have superseded them. Before the discovery of bacteria, people assumed that diseases and even flies arose by "spontaneous creation" near decaying matter. This rule does little more than describe the existence of flies and diseases at the macrobiological level of flies and diseases. A more advanced microbiological model later came along and ushered in modern medicine, despite the antireductionist view of emergence. Castling-type rules may exist in our reality, however—we just have yet to unequivocally find any. Emergent behavior does not need castling-type rules to explain it. More basic rules can explain a complex structure, complete with its own descriptions and concepts. We should also, on aesthetic grounds, prefer to avoid the ad hoc addenda to reality that castling offers in favor of a unified approach that weaves together all the rules.

Emergent structures arise in chess that its fundamental laws can model. Nevertheless, to describe a game of chess to a friend, we would talk in emergent terms, because they offer the best way to describe what occurs. If I say, "g1–f3," my friend may not realize what is going on. If I say, "I moved my knight to f3 so that I can defend my central pawns and threaten the fork on g5," then I communicate more clearly.

Emergent structures in the real universe are similar. They differ because, in Chessworld, with a lot of thought and concentration, we might "read" the emergent structure of forks and pins from a bald report of "g1–f3; b7–

b5; . . ." We cannot do this in our universe; no one has yet told us all the rules. This difference amounts to little. Our computational powers may stretch to "read" forks, but no one knows the best move in a game until just before checkmate. Every chess game played in recent centuries starts with the pieces in the same positions, but nobody knows the best first move. We notice the tactical quality of a move—some moves just surpass others—but we cannot nail this down. We are sure, however, that the rules of chess can model all that happens.

Game of Life. Some mathematicians focus not on chess but on cellular automata, because it is easier to program them on a computer. John Conway's automaton, "Life," consists of a two-dimensional grid of black and white squares (or cells). If and only if three neighbors are black, a white cell turns black; this represents a "birth." A black cell survives so long as either two or three adjacent cells are black. It otherwise reverts to white. The system evolves in steps: each cell looks at its neighbors and decides how it will behave; then the cells all change simultaneously; then they look at their neighbors again. That is it. This "Game of Life" need not result in a screen of static. Dynamic but stable solutions sometimes emerge alongside fixed patterns. The dynamic designs can be simple, commonly flashing hollow "diamonds" of four cells. The designs can also be complicated. One pattern, the "flyer" or "glider," looks like a winged plane of black cells that glides diagonally across the map (Figure 1). The glider shifts one space forward for every four moves and so, over time, flies from one corner of the universe to another. Something new emerges here. The rules of the Game of Life do not contain the idea of movement or transition, but the game creates structures that move. This movement, in turn, suggests the possibility of transmitting information from one region of the cellular map to another. Mathematicians ask what kind of computations they might achieve this way. They discover that, by using gliders as carriers of simple bits of information, they can build a Turing computer. An arrangement of black and white cells can, therefore, compute anything the latest Pentium processor can.

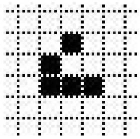

Fig. 1. Conway's glider.

Two sentences describe the rules of the game: (1) The Game of Life consists of a two-dimensional grid of black and white squares (or cells). (2) If and only if three neighbors are black, a white cell turns black; a black cell survives so long as either two or three adjacent cells are black; otherwise, it reverts to white (Seife 1994).

These rules can model anything a computer programmer can produce. Emergence is here; the units of black and white cells make up gliders, the information transmission units of gliders make up the computer, and the computer can model any computable environment. The dynamical structures of the Game of Life obey rules with no explicit relationship to the game's program. They seem to operate at an entirely different level of reality inside the computer program. The Game of Life betrays not just the semblance but the reality of emergence—an emergence that stems from a few simple commands in machine code. When this happens and the cells form a computing pattern, however, the whole grid does not act significantly in a downward way on individual cells. They merely follow the two sentences of rules, paying no attention to the whole. Yet, the whole executes computer programs that we could never fathom if all we saw were snapshot descriptions of the black and white cells. A cellular description of how the Game of Life computes lies beyond us. But we know how it does it. We have a model.

CHAOS AND CRITICALITY

Per Bak, Kan Chen, and Michael Creutz's work bridges this mathematical theory to our real universe. They study many variations of Conway's system, focusing on the chaotic stage between the initial arrangement of black and white cells we provide and the stable state that emerges afterwards. What happens when we introduce minor yet random perturbations to disturb stable situations? How, in Game of Life terms, do species adapt to constant yet subtle alterations of their environment? This situation mirrors what occurs in the natural universe. Bak, Chen, and Creutz have found that the activity in the computer program responds in a predictable and nonchaotic way to the stimuli. The resulting activity—measured as the total number of births and deaths, and the duration of disturbances—follows simple laws. "The fact that activity does not decay or explode exponentially [to become chaotic]," write Bak, Chen, and Creutz, "indicates that life and death are highly correlated in time and space: the system has evolved into a critical state" (1989, 780–82).

The emergent patterns in the Game of Life follow fractal mathematics. "We find that fractals describe the distribution of the epicenters of earthquakes. Although fractals appear throughout nature, investigators have only recently begun to understand the dynamics that create fractals. We and our colleagues suggest that fractals can be viewed as snapshots of self-organized processes. Fractal structures . . . are the spatial fingerprints . . . of self-organized criticality" (Bak and Chen 1991, 26).

Fractal patterns fill the natural universe, from the twisted shapes of the oldest trees to the crystals of a newly formed snowflake. Bak and Chen have researched different computer models—simulating forest fires, earthquakes, economies—and always fractal patterns emerge, as in the real universe—with often unpredictable results. They call these emergent states "critical."

We might expect that systems modeled this simply would, when disturbed, move in proportion to the disturbance. Kick them hard and they respond wildly; touch them softly and they hardly change. Not so. Like our experience of unexpected earthquakes and fragile ecosystems, the opposite can occur in Bak and Chen's models: "Systems as large and complicated as the earth's crust, the stock market and the ecosystem can break down not only under the force of a mighty blow but also at the drop of a pin. Large interactive systems perpetually organize themselves to a critical state in which a minor event starts a chain reaction that can lead to catastrophe" (Bak and Chen 1991, 26).

This leads to a creativity inherent in the universe. Novelty arises when causes cannot contain their effects. Introducing tiny fluctuations into the lawlike evolution of processes can, under chaos, magnify into novel macroscopic effects. Unchecked, chaos can grow to become a destructive infusion of randomness. But some dynamic structures can walk a tightrope between chaos and stasis, restricting the channels by which overly destructive chaos enters the system. This is called self-organizing criticality. Chen and Bak discovered a mechanism by which stable structures can arise from basic beginnings.

Self-organized criticality provides one mechanism for emergence. While still a young area of research, already Bak's and Chen's simulations link it with many natural situations, such as turbulence, evolution, termite behavior, economics, and magnetism. Its discoverers' hope that "the theory of complexity and the theory of criticality may be one and the same thing" (Bak and Chen 1991, 27) may be overly optimistic. Nevertheless, the nonlinearity of many natural systems enables Bak and Chen to exploit the creativity of mathematical chaos. We cannot describe these emergent systems in terms of their parts—in principle as well as in practice—yet we can fully explain them mathematically.

We picture the universe scientifically as a law-governed place where matter and energy flow according to mathematical rules. Any property of mathematical rules will, therefore, influence our understanding of the universe. Emergence, as we understand it, exists in mathematics. Emergence in reality follows the same path.

NUANCES OF MEANING

While scholars cite the existence of emergent objects as proof against reductionism, the study of emergence is fast becoming the foundation of reductionism. We discover how emergence works—and it turns out that many varieties of structure flow from a few simple rules.

This work bridges a divide that many commentators have considered—and still consider—absolute: on one side reside the reductive models of a lower-level science; on the other side flower emergent phenomena. Between the two lies chaos: some phenomena that emerge at the macroscopic level are so sensitive to slight alterations in their underlying microstates that we cannot read the emergent behavior from their microscopic descriptions, or vice versa. None but the highly skilled can follow the strategic development of a game of chess from a list of moves; in the natural universe, where chaos enters the equation, no one can accomplish such a task. We cannot in our heads leap from a description of the universe at one basic level to a description of the universe at a higher level. We are not that smart. Given the huge computational resources required, no finite being is that smart. That game is over.

We can play a different game, however. We can build models of the universe at one level of description, and as we play with them we may discover patterns and structures we did not put into them. We find, from the simple models of quantum mechanics, that we can uncover much chemical structure. This is a genuine discovery; physicist Erwin Schrödinger and his associates did not devise their theory with their chemistry-department colleagues in mind. Newton did not notice a consequence of his own theories, namely, the gravitationally assisted "boosts" whose discovery helps in the exploration of space. Bak and Chen show that we can build and play with chaotic models of reality and, with them, find an array of emergent structures. The chaos that supposedly divides lower-level science from emergent phenomena presents no barrier to mathematical modeling. It presents no barrier to scientific explanation.

Influence Revisited. We can explain—in the scientific sense of "mathematically model"—phenomena that we cannot in principle describe exhaustively. Emergent phenomena fall into this category. The laws of physics do try to model reality completely. Murphy implies otherwise, because she suggests that the universe obeys various laws, including emergent ones, and that the laws of physics "merely" constrain all phenomena (Murphy and Ellis 1996).

What might "'merely' constrain" mean? That phenomena can mostly do as they please (that is, behave according to chemical, biological, and social laws) so long as they observe the laws of physics? Emergent or downward behavior influences or restricts the actions of parts over and above their "normal" behavior. This misrepresents the nature of scientific laws; they do not proscribe, as in a legal system, laying out what cannot be done while leaving freedom for legitimate behavior. Scientific laws model what *is* done. That the laws of physics constrain all phenomena really means that the laws can model the phenomena.

Are "whole-part constraints" the only viable explanation for emergent phenomena? Peacocke writes of the mind-body problem and of his notion of the mind causing events within the brain:

> The point which has to be emphasized in the present context is that this whole state of the brain . . . acts as a constraint on what happens at the more specific level of the individual, constituent neurons, so that what occurs at this lower level is what it is because of the prevailing state of the whole. In other words, there is operative here a top-down causation between the level of the brain state as a whole and of the individual neurons. (Peacocke 1993, 60)

This example of downward influence shows the usefulness of the idea. We can conclude certain things about a person's neurons given knowledge of her or his brain state. If we know a person is catatonic, we would expect most of his or her neurons to be inactive. But this need not imply that the catatonic state causes the inactivity of the neurons. The "constraint" in "whole-part constraint" goes too far. Even if we accept catatonia and neuron inactivity as two qualitatively distinct conditions, some common cause still might result in their coincidence. A law of downward influence between brain states and neurons explains nothing, because it offers no substance for a scientist to investigate. Science does not link the two. Rather, our logic links them: we draw conclusions about the parts of a system from information about it as a whole. From the fact that I feel hungry—a mental event—I conclude that my stomach is empty—a biological condition. This does not mean that my idea of hunger caused my stomach to empty. Quite the opposite. A state of catatonia does not cause the inactivity of neurons. Quite the opposite. A state of catatonia offers a valid description of what happens. But simple descriptions are not the be-all and end-all of explanation, nor should they initiate our ontology. Descriptions are simply what we can say about the universe. Ontology studies the deeper question of how these descriptions take the form they do.

Peacocke believes the irreducibility of higher-level descriptions establishes the existence of downward influence:

> On the critical realist view of the epistemology of the sciences, this has the further implication that the entities to which the "theories and experimental laws" refer in our epistemological analyses correspond . . . to realities which must be deemed to exist at the various levels being studied—that is, they also have an ontological reference, however elusive. . . . So it is legitimate to describe the realities postulated as existing at the higher levels (the wholes, the "top" of the "top-down" terminology) to be causally interactive, in both directions, with the realities postulated as existing at the lower levels (the parts). (1993, 54)

This can lose the heart of "influence." Molecules in the Bernard cell line up. But to say the cell influences the regularity abandons the search for a deeper explanation. If we had a valid lower-level explanation, why say the cell influences the regularity? Since we have a valid explanation at the cellular level, why say the glider or the game influences the glider's movement in the Game of Life? Peacocke is right if higher-level descriptions offer the best possible explanations of what occurs. But science never assumes it has found the best explanation for any phenomenon and always seeks one at a lower level. We may, from the fine structure of a glider, uncover creation and annihilation rules that the cells in the Game of Life obey. We will probably uncover deeper explanations of the Bernard phenomenon in due course. These will offer qualitatively better explanations than downward influences can; they will provide more useful, more general, and simpler models of reality, which we can use to discover yet more about the universe. This reflects something about the structure of reality, something about the fertility of mathematical patterns and the comprehensibility of physical laws.

Many patterns and regularities in the universe do not feature explicitly among the laws of physics, but the laws explicitly or implicitly contain every possible physical behavior. This provides an insight into the structure of reality. Physical terms may not describe all biological laws, but the set of models that is biology comes solely from the sets of models that are chemistry and physics. We ought not to extol the former of these points (many patterns and regularities in the universe do not feature explicitly among the laws of physics) and eclipse the significance of the latter (the laws of physics explicitly or implicitly contain every possible physically behavior). To do so throws out—along with extreme reductionism—the constructive, model-building ontology at the heart of science.

EMERGENT DIVINITY

Peacocke's analysis of emergent phenomena successfully refutes the radical reductionism that would trim down all higher-level descriptions of reality to stories told in the language of physics. Such reductions are impossible and undesirable. Peacocke then explores the consequences of downward influence and uses the idea to counter the less radical reductionist idea that we can understand the emergence of structures and patterns in reality in terms of more basic and general structures and patterns. In this second refutation, Peacocke may err. Ideas about influences and causality follow our models of reality, not our descriptions. The two differ. Peacocke shows that we cannot indefinitely reduce descriptions to lower-level forms, but he does not show this for models of reality. The science of emergence shows the opposite and thus supports the less radical reductionism.

Peacocke's thoughts about emergence move usefully into the theological arena and our above conclusions extend into his spiritual thought. First, he attempts to justify theology as a valid discipline and arena of study:

> These reflections led me to perceive how theology (talk about God: theo-logy) might be given at least a provisional justification by locating it on this map of knowledge. . . . At the topmost limit of the scale of complex relations in any schema, one cannot but place the relation of God to the world and to human persons in the world (possessing as they do the most complex piece of matter in that world, the human brain). . . . From the map we have been outlining . . . the language needed to articulate these relationships should be distinctive and sui generis. . . . Thus theology can find a legitimate location on such a map and the terms in its theories

> (usually called "doctrines") can refer to realities and are not prematurely to be reduced to those of, say, psychology, anthropology, or sociology. (Peacocke 1994, 649)

Murphy writes that "Peacocke [claims] the hierarchy [of sciences] needs to be completed by considering theology to be the topmost science" (Murphy and Ellis 1996, 19). Peacocke may not endorse her analysis, but it does expose an omission. Focusing on the hierarchy of sciences can detract from seeking an explanation for its structure. Peacocke draws conclusions about reality from only the existence of the hierarchy. New work on emergence points to explanations for the hierarchy that lie at a deeper level, and they tell a different story.

In spite of this, Peacocke does succeed in justifying spiritual thought as a valid discipline. We do not seek to justify spiritual thought as a science; we seek the fate of all higher disciplines in the light of the reductionist program. Peacocke shows their validity. They do yield genuine and useful knowledge of the universe. He also shows that emergence guarantees the usefulness of these higher-level descriptions, irrespective of future discoveries. If spiritual language sits atop the scale of descriptions of human experiences, it and its truth are as valid and significant today as they always have been and always will be.

Peacocke aims his project further than this. Emergence provides for him an explanation for the interaction between divinity and reality. The problem of divine action in the universe revolves around the issue of providence. It does not concern the Divine's sustaining presence within each and every event but rather the Divine's capacity to act providentially to direct the universe as the Divine sees fit. Christians repeatedly describe their god as the instigator and cause of events in the universe, and Christian scholars must now understand this within the framework of modern science. Peacocke attempts it with his idea of downward influence, a metaphor that pictures the Divine acting via the universe-as-a-whole downwardly to influence its evolution. How would we perceive such activity locally? Such an influence, Peacocke agrees, cannot lead to any part of the universe breaking the laws of physics. He therefore invokes a "flow of information": "A general concept which has often been found to be applicable to understanding the relation between higher and lower levels in a single, hierarchically stratified complex is that of there being a flow of information from the higher to the lower level whereby the higher level constrains and shapes the patterns of events occurring among the constituent units of the lower one" (Peacocke 2000, 225).

Contrary to the general perception, however, information is physical. Information transfer must involve a physical process subject to the laws and restrictions of physics. Peacocke seems aware of this: "although information is a concept distinct from that of energy and, of course, from matter, yet, in actual systems, no information flows without some exchange of energy and/or matter" (2000, 225). He then refers to information flow as "an interpretive concept. . . . This process can at least be conceived as a process of transfer of information, as distinct from energy or matter" (2000, 225). Transfer of information involves energy or matter, Peacocke admits, and yet he also thinks of it as distinct from energy or matter. Yes, the ideas are not interchangeable and in that sense are distinct. But one cannot exist without the other. Information must entail a physical realization or it does not exist. Peacocke probably means one of two things. Either the Divine injects nonphysical information into the universe, or the universe-as-an-emergent-whole holds physical information that its parts do not. In the first proposition, the Divine violates the laws of physics—an idea Peacocke would not support. He would probably opt for the second idea that emergent wholes, in particular the universe-as-a-whole, possess information that their parts do not possess individually. This offers a physical, testable claim. It is inaccurate, for the reasons outlined in this essay. We can model emergent wholes as systems of interacting individual parts. The sum total of the information the parts possess equals the information the whole possesses. This suggests that emergent systems are not holistic in the sense of the whole influencing the parts in ways the parts cannot do by themselves; quite the converse, they emerge from the interactions of their parts.

John Polkinghorne suggests that the existence of chaos in natural laws signals an ontological openness in nature. The input of active information into chaotic systems, undetectable to a finite being, could explain how divine action works. Peacocke's proposal uses information input in the same way. Emergent reality depends, he thinks, on the irreducibility—due to chaos—of one level of description to another. He thus provides a mechanism for Polkinghorne's metaphor. Peacocke's model reduces to Polkinghorne's god of ontological chaotic gaps, of which Peacocke is rightly critical. The mechanism lacks physical meaning.

HOLISM

Peacocke believes we can understand emergent structures holistically. They act as coherent wholes, both on one another and, more crucially, on their parts. He wants us to understand the laws of downward influence holistically and, thus, to see how they defy reductionism. We have suggested that his program does not work. There is nothing wrong with holistic causal laws; there is nothing "unscientific" or "unphysical" about them—only, as nature and mathematics teach, emergence does not exhibit holism.

One scientific theory does exhibit holism: quantum mechanics, the most "fundamental" theory that physicists possess. The difficulties with realist interpretations of the theory suggest that we should not pursue ontological conclusions from it. Nevertheless, major differences separate the holism of entangled systems in quantum mechanics and the holism of emergent systems:

- The parts of a quantum system exhibit behavioral correlations regardless of their spatial separation, and experimentalists can observe them. However, the parts of an emergent system exhibit no quantum correlations.
- A measurement on a significant fraction of the parts of a quantum system yields almost no information about the total state of that system at any level of description. However, knowledge of the location and orientation of a significant number of molecules in a Bernard cell reveals a great deal of information about what goes on with the cell.
- We require a new theory of computation and information to cope with the changes that quantum entanglement implies. However, any modern Turing computer can simulate simple emergent phenomena.

Holism provides a powerful metaphor for divine presence and action in the universe, but we must employ it carefully and precisely. Holism no longer lies only in the province of the metaphysician; it has become a facet of physical theory and an object of study for scientific theoreticians. The success of reductionism in science lies in the discovery of complex whole structures emerging from seductively simple models. Simple parts do sum to wonderful wholes.

Conclusion

Peacocke writes that all we might say about reality exceeds physics:

> While recognizing that the constituent units of a complex whole (such as atoms and molecules in a living organism) obey their relevant laws at their own level, there is indeed much more to be said. It may be true even that the Archbishop of Canterbury is 59 percent water, but so also are General Amin, and the latest Nobel laureate. There is something more to be said, even if one does not want to say that there is some special entity present in living organisms. (1976, 315)

We suggest something more. We can describe the archbishop from a biological point of view—as an older human male—or from a social point of view in terms of his influence on British people. We can even describe him spiritually in terms of his relationship to his church and to his god. These all offer valuable descriptions. But none shows any kind of causation and activity that physics cannot model. Physical models fail to describe every phenomenon exhaustively, but they do explain the form of descriptions. No science can claim to encapsulate all that we might say about the universe, but all sciences can hope to explain how we might express what we can say. This constitutes the reductive role of all sciences in relation to emergent phenomena beyond their current explicit reach.

Physics, chemistry, biology, sociology, and theology are valuable for describing and explaining our experiences as humans. We can analyze, depict, and study the universe in different ways. Yet, the universe can also behave coherently and comprehensibly. The study of emergence helps us understand this mystery. Emergence does not suggest that our comprehensible universe is a menagerie of substances and laws, an interlocking of levels and causal chains. Emergence teaches the reverse. The levels—and all the wonders and harmonies of creation—emerge from one coherent set of physical principles.

NOTE

We wish to thank Arthur Peacocke for his most helpful comments on an earlier draft of this essay.

REFERENCES

Bak, Per, and Kan Chen. 1989. "The Physics of Fractals." *Physica D* 38:5–12.

———. 1991. "Self-Organized Criticality." *Scientific American* 261 (1): 46–53.

Bak, Per, Kan Chen, and Michael Creutz. 1989. "Self-Organized Criticality and the 'Game of Life.'" *Nature* 342 (14 December): 780–82.

Murphy, Nancey, and George F. R. Ellis. 1996. *On the Moral Nature of the Universe*. Minneapolis: Fortress.

Peacocke, Arthur R. 1976. "Reductionism: A Review of the Epistemological Issues and Their Relevance to Biology and the Problem of Consciousness." *Zygon: Journal of Religion and Science* 11 (December): 307–34.

———. 1979. *Creation and the World of Science*. Oxford: Clarendon.

———. 1993. *Theology for a Scientific Age.* Enlarged ed. London: SCM Press.

———. 1994. "The Religion of a Scientist: Explorations into Reality." *Zygon: Journal of Religion and Science* 29 (December): 639–60.

———. 2000. "The Sound of Sheer Silence: How Does God Communicate with Humanity?" In *Neuroscience and the Person: Scientific Perspectives on Divine Action*, ed. R. J. Russell, N. Murphy, T. C. Meyering, and M. A. Arbib, 215–48. Vatican City State: Vatican Observatory, and Berkeley: Center for Theology and the Natural Sciences.

Seife, Charles. 1994. "Mathemagician. Presenting the Legendary John Horton Conway: Trickster, Group Theorist, Inventor of the Game of Life." *The Sciences* 34 (3): 12–15.