10.
Shining Through?

The Astonishing Hypothesis is that "You," your joys and your sorrows, your memories and your ambitions, your sense of personal identity and free will, are in fact no more than the behavior of a vast assembly of nerve cells and their associated molecules."

Francis Crick[1]

The Burden of Disproof

As I write this, the twentieth century is drawing rapidly to a close. The media soon will be saturated with articles and documentaries looking back at the many events that have marked this turbulent period in history. We can easily imagine the stories about the Beatles and Elvis, Charlie Chaplin and Marilyn Monroe, Babe Ruth and Jackie Robinson. Future historians, with greater hindsight, will focus more attention on Gandhi, Lenin, Hitler, and perhaps Einstein. They will undoubtedly point to the World Wars, the end of empires, the failed experiment of communism, the population explosion, the environmental crisis, space travel, and other largely political events that marked the century as a watershed.

Surely these historians will not fail to note that the unprecedented force of these dramatic events was a direct consequence of the rapid development of science and technology, continuing the trends of the centuries since Galileo and Newton. With modern technology has come both the means for mass human expansion and mass human destruction.

Science has proven itself to be the mightiest activity ever undertaken by the human race. What other enterprise can you name that has had within its reach sufficient power to destroy all life on this planet? No doubt, science has great potential for disastrous misapplication. But on balance, most people would rather live with it than without it. After all, who would want a tooth pulled by a shaman when a dentist, using the novocaine developed by much maligned Western science, can do it painlessly?

Technology has resulted in unprecedented, if unevenly distributed, wealth. It has given its beneficiaries longer, more fulfilling lives that are largely free of physical pain and suffering. Undeniably, many billions have not shared in this largesse, but the other billions who have enjoyed the benefits of science constitute, by themselves, a greater number of human beings than have lived on this planet in the entire period prior to the twentieth century.

As a result, many people have come to look to science to solve all their problems. Worried about nuclear missiles? Let science build a shield. Fretting about running out of oil? Science will find us an endless source of energy, perhaps cold nuclear fusion. Too little food? Science will grow more. Too many people on earth? Science will launch them into space. Too much pollution? Science will find a way to clean it up. Sick? Science will heal you. Feeling depressed because you are going to die someday? Science will find a way for you to live forever, if not by medical means, then perhaps by confirming your deeply-felt belief that your selfhood is intimately connected to the very fabric of reality.

How wonderful, most say, that science makes our lives so comfortable. And how wonderful, some say, that science has confirmed our long-held belief that human consciousness is the driving force behind the universe itself!

Quantum mechanics is arguably the greatest scientific theory every invented. It has provided us with many of the tools of modern technology, while describing matter at its most fundamental level. Some believe that quantum mechanics has done even more, demonstrating that an act of human consciousness at one point in space can instantaneously cause a material system to change its behavior, indeed its very nature, at a distant point in space - even across the whole universe. And not just instantaneously. Human consciousness, they say, can cause changes at other points in space even *before* the thought occurred. After all, that thought is part of the unbroken wholeness of all existence. The mind exists throughout all space and time. It always existed, and always will exist.

This is the profound implication that many believe to be confirmed by the experimental violations of Bell's inequality. The popular literature abounds with this theme as paranormalists of every stripe from psychics to astrologers to physicists and cosmologists proclaim the oneness of human mind and the fabric of the cosmos.

While articles in scientific magazines and journals often blazon the wonders of quantum nonlocality, they rarely carry the story through to its bizarre conclusions. That is left to the authors of metaphysical books. But scientists and the science media cannot continue to ignore their responsibilities, if they are to remain reputable. By their avoidance of the sticky issues raised by nonlocality and the quantum consciousness, they effectively help promote a pseudoscientific interpretation of quantum mechanics that is not demanded by data or logic.

The notion of a holistic universe, with everything instantaneously connected to everything else, occurs in a number of interpretations of quantum mechanics. If still-undetected forces operate on particles to determine their quantum mechanical motion, these forces must necessarily be nonlocal, according to the implications of Bell's theorem. It would appear inescapable - the universe is one and we are one with it.

But as we have seen, no empirical or theoretical basis can be found to support this assumption. Nonlocality is not required by the data; superluminal motion has never been observed.[2] Experiments that have tested Bell's inequality are fully consistent with six-decade old conventional quantum mechanics, reductively interpreted without the metaphysical baggage of collapsing wave functions, nonlocal hidden variables, or parallel universes. Nonlocality only enters via interpretations that assign ontological meaning to mathematical objects like the wave function, which play only an epistemological role in the physical theory of quantum mechanics, or demand the existence of deterministic sub-quantum forces.

Similarly, while "unconscious" instruments undoubtedly record quantum effects, "consciousness," human or otherwise, however defined, is not required to play the active role in quantum mechanics that some have suggested, namely provide the mechanism for wave function collapse.

Undoubtedly, quantum mechanics has had difficulty in gaining a consensus on how it should be interpreted - or even that it need be interpreted at all, so long as its mathematics works. Many interpretations have been proposed that lead to the same empirical results, and so are indistinguishable except by their formal structures. Without experiment to provide its traditional, (usually) unambiguous adjudication of scientific disputes, it becomes somewhat a matter of taste which interpretation one prefers.

Not all interpretations of quantum mechanics are equally economical, or equally useful. For example, the claim that human consciousness plays a role in determining the outcome of experiments is not parsimonious since it is not required by a scrap of reliable data. Likewise, nonlocal hidden variables theories are uneconomical, proposing as they do invisible holistic entities having superluminal connections for which no direct or indirect evidence exists.

The many-worlds interpretation is not parsimonious because, well, it has many worlds, at least when all the parallel universes are viewed as "equally real." The transactional interpretation, on the other hand, is somewhat more parsimonious than these others, but still requires the uncomfortable idea that a detector continually sends out "confirmation" waves backward in time.

More generally, we have seen that the paradoxes of quantum mechanics disappear once we recognize that elementary processes do not distinguish between past and future or cause and effect. While this violates our common intuitions, those intuitions are based on our experiences in a world of many particles in which phenomena that are fundamentally statistical behave very predictably because their probability distributions are highly peaked around the most probable outcome. Thus our notions of case and effect and the direction of time are principles invented to describe the macroscopic world of our experiences, not the quantum world.

We have seen that the *alternate* (or *consistent* or *decoherent*) *histories* interpretation of quantum mechanics, which grew out of many worlds and the earlier path integral formulation of Feynman, offers a local, reductionist, non-deterministic, and economical answer to the apparent paradoxes of quantum mechanics.

Some will dispute my statement that alternate histories is local. I admit that this is still arguable (if one insists on a fundamental time direction). However, I reiterate my view that until superluminal motion or communication is empirically demonstrated, this dispute is one over theory, not data. Rather than claiming nonlocality in nature we should be seeking a local interpretation of quantum mechanics. Even if this requires making some change in its fundamental structure, we would still be doing less violence to fundamental physics by pursuing this end than by discarding the essential ingredient of modern physics, namely absence of speeds greater than the speed of light.

Without regarding all parallel universes as equally real, alternate histories gives us a simple prescription for calculating the relative probabilities for the various paths a quantum system may take through space and time. Furthermore, it represents a modern, albeit tentative, explication of what really goes on when physicists do quantum mechanics. Within the alternate-histories framework, measuring devices and the environment generate the decoherence necessary to produce the classical paths we observe in our own macroscopic world, where quantum effects are minimal.

However, the issue is not settled. Questions remain about how the choice between histories, and equivalent sets of histories, are made. Some insist that a mechanism must still be discovered that makes this choice. Currently, that mechanism is blind chance, but what is the nature of that mechanism? While the alternate-histories interpretation may not remove all the mystery from quantum mechanics, at least it provides a counter example that disproves the contention that quantum mechanics *requires* either a conscious or a holistic universe - or both.

We have also seen that the phenomena of life and mind likewise provide no basis for the introduction of a non-material component to the universe. Computer studies suggest that the complex matter can spontaneously self-organize into systems that exhibit the properties we associate with life and mind. It seems reasonable that high-level capacities were bound to happen somewhere in the universe in its over ten billion year existence. While the specific form that life took on earth was largely accidental, some form of life was almost sure to happen under the given environmental conditions. Calculations that purport to demonstrate the great unlikelihood of life forming by accident assume, anthropocentrically, that only one form of life, namely ours, is possible.

I do not mean to imply that life is likely to evolve on a large fraction of the planets in the universe, or that intelligence is likely to evolve in a large fraction of these. The evidence from our own solar system, and the absence of signals or probes from extraterrestrial civilizations (UFOs notwithstanding), indicates that life and intelligence requires conditions that are quite rare in the universe. And, even if life is somewhat common, complexity and intelligence are less likely to be so. Paleontologist Stephen J. Gould has argued that life is not necessarily progressive, and the formation of complex life forms may be more of a fluke than the inevitable result of evolution.[3] But the universe is a vast place, and rare conditions have ample opportunity to occur by chance. Computer simulations indicate that complexity can develop by chance.

Mutually interacting, nonlinear systems poised at the boundary between order and chaos are highly susceptible to the Darwinian selection processes that so powerfully direct evolution toward adaptive behavior. The systems being simulated are purely classical, implying that quantum mechanics may play a minor role at best in these processes.

In all of this I may have oversold my case. Undoubtedly some of the views I have presented will be modified by myself and others as time progresses. Someday, some specific example or argument may be shown to be wrong. However, I have confidence that my basic conclusions will stand the test of time. These conclusions do not rise or fall on every statement made in this book.

I maintain that I do not have the burden of disproof. Nonmaterial, superphysical explanations for any given phenomenon cannot reasonably be introduced until all more economical explanations for that phenomenon are ruled out to the highest degree. I merely have to show, as I believe I have, that plausible explanations of all current data can be found within conventional, reductionistic, local, materialistic science including quantum mechanics. I do not feel compelled to validate these explanations, such as by generating life in the laboratory, or performing an experiment that rules out all but a local, unconscious interpretation of quantum mechanics.

Platonic Truths

But have I covered all the metaphysical bases? Perhaps not. In a pair of recent books, cosmologist Roger Penrose has argued forcefully, and controversially, that the human mind is capable of reaching into a realm of reality that lies beyond time and space, a Platonic world of timeless mathematical truth that many physicists still seem to think exists.

Penrose first introduced this view in a widely-read 1989 book, *The Emperors's New Mind.*[4] Though filled with many unnecessary and irrelevant technical details that surely daunted the average reader, *Emperor* briefly made best-seller lists and caused quite a stir.

Penrose has now followed up with *Shadows of the Mind.*[5] While *Shadows* goes over much of the same ground as *Emperor,* the exposition is much clearer and to the point, with the author making a serious attempt to address each specific criticism of *Emperor* and to consider the implications.

In both books, Penrose bases his argument on the issue of whether a computer can ever duplicate all the thinking processes of human beings. In *Shadows* he summarizes four different viewpoints:

A. All thinking is computation; in particular, feelings of conscious awareness are evoked merely by carrying out the appropriate computations.

B. Awareness is a feature of the brain's physical action; and whereas any physical action can be simulated computationally, computational simulation cannot by itself evoke awareness.

C. Appropriate physical action of the brain evokes awareness, but this physical action cannot even be properly simulated computationally.

D. Awareness cannot be explained by physical, computational, or any other scientific terms.[6]

View A is the view of **strong AI** (Artificial Intelligence) or what is termed **functionalism**. In view B, awareness is still a physical process that can be simulated computationally, but this simulation is not in fact awareness. Penrose does not say how one could distinguish a simulation from true awareness, but this is not his position anyway. Rather he holds to view C in which awareness cannot even be simulated computationally.

In *Shadows,* Penrose is careful to distinguish his position from view D in which awareness is not amenable to scientific study and thus must be mystical or supernatural. He says: “I reject mysticism in its negation of scientific criteria for the furtherance of knowledge.” I take this to mean that if awareness is something that can be understood scientifically, then it might still be possible for it to be simulated. It just cannot be simulated, in Penrose's view, *computationally*. Some kind of non-computational machine, made of matter and operating purely in the physical domain, would have to be devised to simulate awareness.

Clearly D is the common religious viewpoint of a dual universe of matter and mind, or body and soul. In my previous book *Physics and Psychics,* I argue that no empirical or theoretical basis exists for this view.[7] Penrose agrees, asking why, if D is correct, "our minds seem to be so intimately associated with elaborately constructed physical objects, namely our brains."[8] Thus Penrose tries to distance himself from what was beginning to be referred to as *Penrose mysticism.* Whether he will succeed remains to be seen.

If awareness is a physical phenomenon that is not computable, that is, a property that a computer (though not necessarily some other physical system) can never simulate, then some change in our physical world-view is required to encompass a new, non-computable physics. That is, some new kind of physics is poking its head through the thoughts in our own heads.

In the second part of *Shadows*, Penrose speculates about the direction that new physics will take. He repeats, in modified form, the notion he promoted in *Emperor* that new physics will be found in what he calls the **R-process**, that is the process of **wave function reduction**, which throughout this book I have called *wave function collapse.* He labels the new process **OR** for **objective reduction**, making clear that the process goes on independent of human involvement. He rejects the notion that human consciousness is the agent of wave function collapse, and by implication, the seat of the new physics.

Penrose believes the key to the new physics lies in quantum gravity, which somehow disentangles spatially-separated, coherent quantum states. Actually, this sounds very much like the decoherence by the environment we have been talking about, where for Penrose the environment is the basic spacetime structure of the universe. However, he does not prove this mechanism is non-computational, and only speculates on what it can possibly have to do with human thinking. I personally find it incomprehensible that quantum gravity, which only comes into play at the Planck scale, can have a profound role on the scale of biological processes. I also find it rather anthropocentric to think that the next great revolution in physics will be found in the human body.

Penrose insists that the evidence for the **OR** process is to be found in human consciousness, even if consciousness is not its source. Of course, the thesis that the brain is not simply a computer is one that the average person will grasp with open arms. Few can imagine, or want to imagine, how a computer can ever have "feelings" and "spiritual experiences."

Wisely, Penrose makes only a cursory attempt to justify his view on the basis of prevailing popular opinion. Neither does he rely heavily on examples of the admitted stupidity of today's computers, despite their power in some areas, and the limited success of the Artificial Intelligence program. Still, he can't resist giving an example of how the chess program *Deep Thought* failed to make a move any neophyte, grade-school player would have immediately seen. He uses this as an example of how computers simply do not seem capable of "understanding."

Penrose understands that computers are in their infancy and that attempting to predicting tomorrow technology is a fool's game. So he rests his case, in both books, on the argument that mathematics contains truths that are not computable. In obtaining these truths, Penrose claims, mathematicians peer into the Platonic realm of true forms to gain insights that no computer can ever duplicate. Although a mathematician may go through a complicated chain of reasoning that is for the most part computable, or *algorithmic,* that chain inevitably contains elements of "obvious knowledge" that are assumed to be valid, that are self-evident truths. Furthermore, these mathematical insights are not just limited to mathematicians, but occur naturally to human children as they instinctively learn the meaning of numbers.

Penrose seems to agree with philosopher John Searle, who has argued that computer "intelligence" is fundamentally misguided because computation is mere syntax without semantics, symbols that have no reference to the real world.[9] Neuroscientist Gerald Edelman also views the computational model of the mental process as inappropriate, though he has no doubt that it is biological in nature.[10] And, they all receive moral support from a famous physicist of an earlier era, Sir Arthur Eddington, who said: "We can only reason from data, and the ultimate data must be given to us by a non-reasoning process - a self-knowledge of that which is in our consciousness."[11]

Unprovable and Undecidable

The primary focus for Penrose's discussion of non-computability lies with **Gödel's theorem**, which says that unprovable truths can exist within any formal mathematical system at least as complicated as arithmetic.[12] Gödel's theorem, in his view, demonstrates that "the mental procedures whereby mathematicians arrive at their judgements of truth are not simply rooted in the procedures of some specific formal system."[13] That is, mathematicians are able to develop true propositions by means other than the strict logic of mathematical procedures.

A related theorem was uncovered by the English mathematician Alan Turing in the late 1930s. Turing showed that any mathematical computation can be carried out on a simple idealized computer now called a **Turing machine**.[14] By treating every formal mathematical statement as a number, Turing concluded that all deductive mathematical procedures can be reduced to such a sequence of mechanical operations on numbers, what are called **algorithms**.

Independently at about the same time, American logician Alonzo Church had derived a theorem proving that a logical statement is valid independent of the meaning given to the symbols used in its expression.[15]

Both Turing and Church had in mind trying to solve a problem posed by the German mathematician David Hilbert in 1900 called the *entschiedungsproblem* (decision problem). Hilbert had asked whether a general procedure exists for resolving mathematical questions, and indeed he thought this was the case. Turing and Church, in their differing ways, showed it was impossible. Specifically, Turing showed that no procedure existed for determining whether or not a Turing machine will ever stop and thus solve, in a finite time, a particular problem posed to it. Thus, not only do undecidable propositions exist, as shown by Gödel, but no procedure exists for deciding if a proposition is decidable![16]

While all this threw the world of mathematics into turmoil, you might ask what this has to do with the real world since mathematics is a human invention anyway, a game played by arbitrary rules. If someone proved a theorem showing that it was impossible to prove that certain sequences of chess steps were impossible, no one would suggest that some deep, metaphysical principle had bee uncovered. And proving that it is impossible to prove whether a team can win a baseball game without scoring a run (barring forfeit) would hardly warrant a line on the sport page.

But Penrose argues: "Once it is shown that certain types of mathematical understanding must elude computational description, then it is established that we can do *something* non-computational with our minds."[17] And, if we are to assume that the phenomenon of mind is still part of the physical world, then we are forced to relate mathematics to that world.

Furthermore, mathematics may not be the arbitrary game it seems.   It appears to be deeply connected to the real world.   All our physical theories are expressed mathematically, and surely the basic mathematical operation of counting is fundamental to any concept we use in organizing the data of our senses and instruments.[18] So if we are able to peer into a Platonic realm of mathematical truth, that realm surely relates in some profound way to the physical universe.

Penrose adds: "There is something absolute and 'God-given' about mathematical truth." He admits he is very much a Platonist: "In my own mind, the absoluteness of mathematical truth and the Platonic existence of mathematical concepts are essentially the same thing." In other words, mathematical truths are the reality beyond the appearances.[19] As I have mentioned, this neo-Platonic view has come to be called **Penrose mysticism**, though the author vigorously objects to this characterization, firmly insisting that the non-computational remains amenable to scientific study.

Mystical Matters and Minds

In his book with the catchy title *The Mind of God*, physicist-author Paul Davies has used Penrose's ideas in discussing the possible connection between mathematics and the traditional notions of mystical truths.[20] Mystics have universally claimed direct communication with deeper reality, called variously The One, The Good, God, the Cosmos, Being, and much more. The mystical experience is supposed to open the mind to instantaneous flashes of insight about a realm beyond the senses. Distinguished scientists such as David Bohm and Brian Josephson claim to have found mysticism useful in developing their scientific ideas, and many of the founders of modern physics speculated about the mystical.

Ken Wilber has edited a collection of such writings in *Quantum Questions: Mystical Writings of the World's Great Physicists.*[21] Included are essays by Heisenberg, Schrödinger, Einstein, de Broglie, Sir James Jeans, Planck, Pauli, and Eddington. Wilber interprets the essays as showing that each author was in fact a mystic. However he admits that "these theorists are virtually unanimous in declaring that modern physics offers no positive support whatsoever for mysticism or transcendentalism of any variety."[22] Thus their mysticism, if it in fact existed, did not arise out of their area of expertise. On this matter, their word is no better than any others.

In her unique book *A History of God,* former Catholic nun Karen Armstrong explains how all the great religions of the world, with the exception of Western Christianity (Roman Catholicism and Protestantism), long ago gave up on using rational thinking as a means for obtaining knowledge about the transcendent - if they ever considered it at all.[23] Buddhists, Hindus, Moslems, Jews, and Eastern Orthodox Christians all developed various techniques to rid their minds of rational thought so that they could make contact with what they believed was the transcendent power beyond the material world of the senses.

In *Physics and Psychics* I argued that the feeling of oneness experienced by the mystic is almost certainly a delusion. One can find no independent evidence that the claimed insights obtained in a mystical state have anything to do with objective reality. No one can point to a previously-unknown discovery made in a mystical state that was later confirmed by scientific observation. On the contrary, virtually every claimed mystical, non-trivial revelation about the nature of the universe and humanity's place within it has proven to be grossly wrong.[24]

In Western Christianity, mystics have been largely discouraged or embraced only hesitantly, such as was the case with Francis of Assisi. Instead, the most influential Church leaders have been theologians, such as Augustine, Abelard, and Aquinas (just to mention the A's), who attempted to place their faith on a rational foundation and thus make it more palatable in the Greek-influenced West. But with no empirical facts with which to cement their hypotheses, the result has been a dogmatic insistence on a personal God amenable to human understanding. Armstrong claims that this has led to many of the excesses associated with Western Christianity, as each sect formed its own rationalized image of God and declared all others to be heretical.

Where other religions have left it largely up to the individual to develop his or her own inner contact with the envisaged transcendent, Western Christianity has insisted that their priests or the Bible act as intermediary, that individual human mental processes are not to be trusted. Thus, by relying on reason, the Western churches became the most dogmatic. Reason has its dangers, too!

So where do Penrose's ideas fit into the mystical perspectives of religion? Certainly, Penrose attempts to be completely rational in applying the theorems of Gödel, Turing, and Church to demonstrate that we cannot determine all that is true by computational means alone. On the other hand, he claims that the human mind nonetheless can formulate these truths, and that they have a Platonic reality to them. Is mathematics, despite Penrose's disclaimer, really then a mystical path to truth? Is it not then more like revelation than science, as it goes beyond sensory data and their numerical manipulations? Is the existence of the Ultimate "shining through," despite the complete lack of any physical evidence or any compelling need to introduce metaphysical elements into our most fundamental theories of physics and cosmology?

Most workers in artificial intelligence remain unconvinced by Penrose's assertion that the human mind cannot be simulated by a machine. After publication of *Emperor,* a goodly portion of one issue of the journal *The Behavioral and Brain Sciences* was devoted to a complete discussion of Penrose's ideas. Penrose's own 11-page *précis* of the book was followed by 37 peer commentaries and the author's response to each.[25] At this writing, a similar critique of *Shadows* is being assembled on the Internet by the journal *Psyche.* Virtually every commentary disagrees with most or all of Penrose's conclusions. Penrose, in his responses has studiously attempted to answer each criticism one-by-one, but I believe it is fair to say that he has not achieved a consensus for his views in any of a number of communities, from artificial intelligence to quantum computation and neurobiology.

Daryl McCullough has drawn the following conclusion that I think nicely summarizes the existing consensus:

> "Penrose's arguments that our reasoning can't be formalized is in some sense correct. There is no way to formalize our own reasoning and be absolutely certain that the resulting theory is sound and consistent. However, this turns out not to be a limitation on what computers or formal systems can accomplish relative to humans. Instead, it is an intrinsic limitation in our abilities to reason about our own reasoning process. To the extent that we understand our own reasoning, we can't be certain that it is sound, and to the extent that we know we are sound, we don't understand reasoning well enough to formalize it. This limitation is not due to any lack of intelligence on our part, but is inherent in any reasoning system that is capable of reasoning about itself."[26]

In other words, if computers have limits, then so do people.

Undoubtedly, the issue will continue to be hotly debated and I will not settle it here. For my purposes, however, the following tentative conclusion can be drawn: Even if the human brain is not a computer, this does not imply that the "mind," which is the name we give to what the brain does, has a mystical or metaphysical component. The view that is promoted by Penrose is one in which the brain still does the thinking by means of some physical process that remains to be determined. Whether or not he is correct on the need for new physics, he sees no need to transcend physics - just move it to a new level. And, as we have seen, no scientific observation demands such an interpretation.

Network Thinking

In the previous chapter, I briefly discussed those computer simulation studies on artificial life that indicate how primitive intelligent behavior develops spontaneously when highly interconnected parallel networks are poised at the boundary between order and chaos. Let us now pursue this further, to see how such networks, operating only on numbers, might become capable of at least a good deal of what we label as thought.

Although the generation of language and mathematics may be non-computational at their very sources, and not represented in exactly this manner in the brain, all verbal and mathematical statements can be expressed as sequences of the binary numbers, or bits. The words in this book, for example, exist as bits on a computer disk. The book can be completely reproduced from that disk, though some would argue that only a human mind is capable of extracting its "meaning."

Scientific knowledge is not all that can be expressed numerically. Even a great painting can be reduced to bits and reproduced in its entirety. Since a poem is a string of words, it can also be expressed in terms of numbers. Parenthetically, computers can write quite acceptable poems and indeed have won poetry contests when pitted, without the judges' knowledge, against human contestants. Perhaps a computer can be programmed to recognize computer poetry better than a human judge!

Suppose that a statement, verbal or mathematical, is determined by a sequence of steps that follow some logical rule. For example, if two statements in a row are each true, then the output "true" is generated; otherwise we generate a "false." This is the logical operation **and**. The logical operation **or** would give true if either input is true, and false otherwise. (More precisely, this is an *inclusive* or, what in the vernacular we often write as "and/or"; the *exclusive* **xor** gives true only if the inputs are different. Thus true or true = true; true xor true = false). The negations of *or* and *and* are called **nor** and **nand**. Groups of ands, ors, nors, and nands can be strung together to produce any logical operation. Actually, it can be done with just nors or (that's an *inclusive* or) nands.

The above rules expressed in terms of statements that are true or false can be represented on a normal, binary computer as operations on the bits 1 and 0. Computations can be reduced to these operations. Conversely, we can think of true/false statements as computational. More complex logical statements can be reduced to true/false questions.

Starting with some initial number, or set of logical statements, we thereby determine by our algorithm some final number or final set of logical statements. For example, the initial number may describe a set of primary propositions, such as Euclid's axioms of geometry. The final number may then describe a theorem derived from these axioms, such as the one saying that the sum of the angles of a triangle equals two right angles.

Turing showed the number representing a theorem can always be calculated by a computer (a **universal Turing machine**) starting with the original number representing the axiom. Where do the axioms come from? Penrose would argue that at least some are non-computable numbers, numbers that cannot be generated by a Turing machine. Those who disagree with Penrose would say they come from some higher-level algorithm.

Deterministic events in nature are analogous to the logical operation of a computer - starting with one number and generating, by a series of programmed steps, another number.[27] Seen in this way, the fact that mathematics applies so successfully to physics loses much of its mystery. The mathematical procedures used in most scientific applications are simply logical, algorithmic operations on numbers, and physical measurements are expressed as numbers. How else but with mathematics can we describe operations on numbers? That's mathematics, by definition.

A serial set of steps is not the sole way to proceed from one number to another. A number can be presented as a sequence of 0 and 1 bits at the input of a parallel processor or what is called a **neural network**, a computer that works as an interconnected network of switches in loose analogy to the human brain. The general folklore holds that such networks can be simulated by serial Turing machines. . However, in a recent paper, Hava T. Siegelmann has claimed that a highly chaotic dynamical network called the **analog shift map** has computational power beyond the Turing limit.[28]

Whatever their Turing status, neural networks still have interesting properties when viewed as a complex net of interacting units. The input bit pattern of a neural network can be transformed into other bit patterns based on a programmed response to the inputs to each switch, or "object," where a decision is made on what bit pattern to transmit forward. While each switch may perform mechanically, the studies with neural networks show that network processing, as clearly exists in the brain, often offers a more efficient way to solve many problems than a linear sequence of steps. But, if a neural network can be simulated by a Turing machine, it remains capable of solely numerical (computational) operations.

One possibility that is just beginning to be studied is the use of tri-state or even more sophisticated forms of logic. Recall the discussion in Chapter 3 of James Hartle's scheme for representing the quantum state of an individual system in terms of the three possible answers to the question of whether or not a system possesses a certain property: yes, no, or indefinite. I mentioned that this might be programmed on a tri-state computer.[29]

In what is called **soft computing** or **fuzzy logic**, hardware and software are developed that are tolerant of imprecision, uncertainty, and partial truth.[30] In a simple example, the binary switches of normal computer circuitry can be replaced by switches that return a yes or no according to some probability function. In this manner, the uncertainty that usually accompanies much of decision making can be simulated. The technique of fuzzy logic is being increasingly used in so-called "expert systems" and is characterized by tolerance and low cost.

Fuzzy theorist Bart Kosko has argued that fuzzy logic represents a grand revolution in Western thinking that harkens back to Eastern philosophy.[31] This, like the similar claims we have heard made for quantum mechanics and chaos theory, is somewhat overblown.

Nevertheless, it seems quite reasonable to surmise that the brain operates more in a fuzzy way, rather than in the uncompromising true or false response of binary switches.   But again, since both tri-state and fuzzy logic can be simulated on a Turing machine, such systems remain computable.

Can a serial or parallel processor, operating completely computationally with binary, tri-state, or fuzzy logic, generate the possible non-computable number associated with an axiom? Here it is important to distinguish between the words **computable** and **deterministic**. Classical physics is both computable and deterministic. However, in the conventional view, quantum mechanics is computable while being non-deterministic. Certainly we can imagine systems (the brain?) that may be neither deterministic nor computable, but still physical.

Perhaps we can regard an axiom as a non-determined number that is still computable. Does this finally open a place for quantum mechanics in the processes by which brain produce axiom numbers? Perhaps in the neural network of the brain a quantum fluctuation of one bit is all that is necessary to produce new knowledge, thus leading to a previously unknown, un-derivable idea.

Is the Brain a Quantum Device?

As we have now seen in great detail, consciousness is not needed to explain quantum mechanics. The remaining issue we need to consider here is whether quantum mechanics is needed to explain consciousness. Many authors have speculated that quantum mechanics plays a part in the functioning of the brain. Their arguments vary from the thoughtful to the specious . Neuroscientist Sir John Eccles has presented a dualistic model in which mind exists as an entity separate from matter, initiating wave function collapse that release neurotransmitters at neural junctions.[32] Penrose and his collaborator Stuart Hameroff have more recently proposed the "orchestrated objective reduction" of quantum coherence in the microtubules of the neurons of the brain.[33]

As we have seen in the preceding chapters, the decoherence mechanism of the alternate-histories version of quantum mechanics removes the need to introduce non-physical elements to account for wave function collapse. However, quantum mechanics may still play a non-trivial role in brain processes.

Henry P. Stapp thinks it does: "Brain processes involve chemical processes, and hence must, in principle, be treated quantum mechanically."[34] Following the logic of this argument, we cannot use Newtonian mechanics to calculate the trajectory of a rock tossed in the air - because the rock is made of chemical elements.

Stapp notes that the transmission of signals in the brain are triggered by small numbers of calcium ions at synaptic junctions. As Nick Herbert colorfully describes it, a neural synapse fires when it emits "little bags of drugs" called synaptic vesicles into the synaptic gap. Drifting across the gap, the transmitter molecules contained in the vesicles either stimulate or inhibit the adjacent nerve cell. Vesicle release is initiated by calcium ions that enter the synapse from the surrounding fluid, crossing through channels that are opened in response to electrical signals.[35]

Herbert and others have made order-of-magnitude arguments that they claim demonstrate a likely role for quantum mechanics in synaptic signals.[36] All such estimates essentially come down to an application of the uncertainty principle.

A simple way one can test whether a system needs to be described quantum mechanically is to ask whether the product of a typical mass m, speed v, and distance d that characterize the system is of the order of Planck's constant h. If mvd is much greater than h, than the system probably can be treated classically, barring very special long-range correlation effects such as in EPR experiments.

In the case of synaptic transmitters, m is of the order of 10^{-22} kilogram. Assume v is comparable to the typical speed associated with thermal motions at body temperature, about 3 meters per second. The gap distance d is of the order of ten atomic diameters or 10^{-9} meter. Then mvd = 3×10^{-31} Joule-second. This is to be compared with the value of Planck's constant, h = 6.63×10^{-34} Joule-sec. That is, mvd = 500h, which seems to indicate that transmitter motion can be treated classically to a fair degree of approximation.

Note that the fact that the brain sits at body temperature results in much greater particle speeds than occurs in superconductors, the favorite example of macroscopic quantum systems. Even the so-called "high temperature superconductors" must be cooled far below 98.6 degrees Fahrenheit to function. The high temperature of the brain makes the decoherence mechanism much more efficient and quantum coherent effects very unlikely.

To make a case for quantum effects in the brain, proponents have to squeeze mvd lower by about two orders of magnitude. This can be done with a certain amount of hand-waving. The mass m may be an order of magnitude lower; the speeds have a statistical distribution, and lower values will occasionally happen; the relevant distance may be as low as an atomic diameter in the case of charge-driven, electromagnetic synaptic processes.

On the other hand, the process of neural stimulation is not conducted by a single transmitter molecule. Hundreds of vesicles with thousands of transmitter molecules are required and fluctuations are smoothed out by the homeostatic mechanism of feedback that characterizes most biological entities. Again, the large number of particles involved implies strong decoherence.

Penrose and Hameroff have proposed a new idea that the seat of quantum effects in the brain lies in **microtubules**, hollow fibers that form part of the cytoskeletons of most of the cells of animal and human bodies, not just brain cells.

They suggest these may be the cell's own "nervous system."[37] The diameter if a microtubule is even greater than the synaptic gap, and they are much longer, so they are certainly "macroscopic" objects by the above standard. Penrose suggests that microtubules act in a coherent way, but has no hard evidence to back up this notion. Behavioral neuroscientist Michael Lilliquist has asked why the microtubules in neurons and not those of other cells, say the liver, should alone show quantum effects.

I conclude that, while quantum effects are not obviously required to describe the general motion of synaptic vesicles or other components of the brain's nervous system, room does exist for the possibility that some low probability quantum fluctuation occasionally generates a bit error in the signal transmitted across a synaptic gap. Perhaps this generates the non-computable number Penrose calls "understanding." However, the existence of long-range, EPR-type correlations in the brain seems far-fetched.

The fact that the probability for bit errors in the brain is small is fortuitous. Otherwise, our brains would be unable to function as even semi-reliable information processors. On the other hand, if the probability for bit fluctuations is too low, then this mechanism for the generation of non-algorithmic knowledge will not work.

Of course, most of the non-computable numbers generated by random fluctuations will be of no value. Only the rare fluctuations will reproduce the axioms of geometry or some other original idea that cannot be computed by a sequence of mathematical steps. A great many non-computable numbers would have to be generated and then some selection process, which itself could be perfectly mechanical or algorithmic, would have to act to choose those non-computable numbers lead to useful ideas.

It may be difficult to imagine such a selection process being very efficient, given the fact that the useless bit strings will far outnumber the useful ones. This might strike the reader as unlikely as the monkey at the keyboard writing Hamlet ("To be or not to be, that is the gzetrnamfj"). However, Darwinian selection, as embodied in both natural and artificial life, comprises a highly efficient mechanism for rejecting useless mutations and accepting useful ones. This does not mean that the brain selection process is necessarily Darwinian in detail, just that we already have at least one example where the selecting out of useful mutations from a sea of useless ones does in fact exist.

While quantum fluctuations may be the source of non-computable numbers, they are by no means the only source. The fluctuations that produce non-computable numbers could result from cosmic rays or other interactions between the brain and its environment.

Whatever the source of the fluctuations that give non-computable signals in the brain, if any, we may reasonably view the brain as a neural network on the edge of chaos. A fluctuation can give the network just the nudge it needs to move from one metastable state to another. By operating at the edge of chaos, the network can move between different states and rely on self-organization to provide the selection mechanism to move through what Stuart Kauffmann calls the **fitness landscape**, eventually settling down to a configuration of neurons that contains new ideas to be tested against sensory input from the real world. Quantum mechanics need not be invoked at all.

The Force of Consciousness

Those who promote the myth of quantum consciousness are not content with the trivial possibility that quantum fluctuations may be responsible for introducing a certain indeterminism into the processes of the brain, thus allowing for some non-Newtonian behavior. They refuse to believe that that's all there is to it, that the "mind" does not play a greater role in choosing between the alternative paths that can be taken as the brain moves between metastable states.

This belief is not based on any external evidence. Rather the claim is made that our "inner experiences" of consciousness, wholeness, and self-awareness require something more - a controlling agent capable of dealing with complex wholes. Stapp argues that such control is a logical impossibility "within a framework in which everything is asserted to be nothing but an aggregation of simple parts." Claiming kinship with William James, Stapp adds:

> "In order to accommodate an intrinsically unified thought, as distinct from an aggregation that is *interpreted* as an entity by something else, one must employ a logical framework that is not strictly reductionistic: a framework that has among

its logical components some entity or operation that forms wholes."[38]

Stapp alleges that quantum nonlocality provides him with that framework.

Herbert thinks that "consciousness will turn out to be something grand - grander than our most extravagant dreams." He proposes "a kind of 'quantum animism' in which mind permeates the world at every level" with consciousness "a fundamental force that enters into necessary cooperation with matter to bring about the fine details of our everyday world."[39] However, Herbert does not tell us what makes humans different from rocks, which is the goal of the discussion after all.

In the Copenhagen interpretation, instantaneous wave function collapse occurs during the act of measurement. In the emerging modern post-Everett interpretations, decoherence provides a mechanism for wave function collapse. In l an economical view that remains to be refuted, the event that happens is randomly chosen from the possibilities, according to probabilities calculated from the wave function.

The quantum mystics persist in their belief that human consciousness must act as an agent to bring about the specific choice among alternate paths. The conscious force, in the view of Stapp and Herbert, acts to "actualize" the event, changing a possibility into a happening. To physicist Euan Squires, consciousness interacts with the world in determining the choices between paths.[40]

In these proposals, consciousness collapses the wavefunction, or chooses the path that happens. As Squires describes his model, the mind acts as the "selector" among alternate worlds, the way a TV viewer chooses which channel to watch.[41] Philosopher David Albert has a similar model that he calls the theory of *many minds.*[42]

Penrose also argues for "some kind of active role for consciousness, and indeed a powerful one, with a strong selective advantage" to avoid blind randomness.[43] However, he disagrees with the quantum dualists in an important way. In the dualistic view, consciousness is some kind of extra-physical force that acts to cause events to happen, to collapse wave functions or actualize particular histories. In their view, mind controls the universe.

Penrose, on the other hand, proposes that some new physics is involved in consciousness - but it remains physics. In his view, the universe still controls the mind. Nevertheless, in claiming that new physics can be found in the operation of human consciousness, Penrose joins Stapp, Herbert, Squires and other authors I have quoted throughout this book in assigning a very special role in the universe to what may be in fact a simple accident of evolution.

For, after all, what is "consciousness"? No consensus exists on what that the definition of consciousness should be. When I have mentioned consciousness, it has always been in the context of what other people have said about it, not me. I am very suspicious of words that are difficult to define. They make we wonder if they even need to be defined, when they concepts supposedly represented are so unclear. If consciousness is someday defined out of existence, the arguments I have made in this book would only be reinforced.

At the same time, however, these arguments do not require the non-existence of a purely local, physical phenomenon called consciousness. Such a phenomenon may exist, but the evidence of decades of experiments in the neurosciences now indicates that it is not so profound as we have been led, and have led ourselves, to believe.

Since a detailed discussion of the nature of consciousness would take me far from the focus of this book, I will refer the reader to recent books by Daniel Dennett,[44] Gerald Edelman[45] and Francis Crick.[46] Adam Carley has given a concise summary of an emerging neuroscientific view, expressed in varying forms in these books and others, that consciousness is in fact simply a trick of the brain.[47] In this view, our experience of "consciously" willing an act, such as moving a hand, has little to do with the actual process by which the brain makes the decision to perform that act. Rather, it seems to be an inaccurate recollection that is formed *after* the actual decision is made.

Over a decade of experiments have confirmed that a delay of several tenths of a second exists between a physical action performed by a subject and that subject's report of the time that he became aware of his "free will" intention to perform the act. This is interpreted to mean that the actual decision making process is a complex process in the brain that takes place unconsciously and not at all in the way it is internally perceived. The process is, a fraction of a second later, imperfectly perceived as an act of will.

This is undoubtedly a revolutionary concept that will be intensely resisted by those who find such a minor role for consciousness impossible to accept. The debate will be long and heated, and I surely will not settle it here. My purpose is not to simply add to the already huge volume of words on the nature of consciousness, but rather to address those claims that modern physics has placed the human mind back at the center of the universe - where human ego continues to insist it be located.

My perspective is admittedly that of a physicist, one who insists on overwhelming empirical evidence before accepting any extraordinary claim. As we have seen, the evidence that quantum mechanics either requires the action of human consciousness, or even plays a role in mental processes is non-existent. Certainly quantum mechanics is needed to understand the atoms in the brain. But it is also needed to explain the atoms in a rock, and this implies nothing about rock consciousness.

Perhaps quantum fluctuations cause random bit errors that the brain is able to organize into new operations, but this role is neither necessary nor compelling. The environment can produce the needed fluctuations. The self-organizing capabilities of the brain's nonlinear neural network, operating at the edge of chaos, may be capable of doing all the work of selection of the best path among all possibilities - with no further help from quantum mechanics. In fact, the human brain and body probably evolved with the dimensions it has in order to *avoid* quantum effects.

It seems to be nothing more than primitive, wishful thinking to view consciousness as some supernatural, or at least super-material, psychic force that provides basic control over the choices the universe makes between allowed alternative paths, either inside or outside the brain. Such a theory is verifiable. It should lead to phenomena such as ESP and psychokinesis that violate the laws that constrain matter. But, as described in Chapter 1, psychic phenomena have failed to be verified after 150 years of attempts involving thousands of independent experiments. After all this time, we can safely assume they do not exist.

The Platonic Realm

We have seen that a deterministic universe is only possible within a continuum of space and time. The motion of a body can be determined only when the body has a well-defined position and velocity at every instant. However, two instants are required to specify a velocity. In classical mechanics, a fundamentally non-measurable *instantaneous* *velocity* is defined by a purely mathematical process in which the time interval is imagined to go to zero. This abstract technique, the infinitesimal calculus independently invented by Newton and Leibnitz, has proven to be the most important implement in the scientist's theoretical tool box.

The laws of classical mechanics and many of the principles of quantum mechanics are composed in the form of **differential equations** that contain the abstract entities of calculus. These include the various forms of the generalized equations of motion, Maxwell's equations of electromagnetism, and Schrödinger's equation. This set of differential equations are so simple, elegant, and powerful that most physicists regard them as the ultimate description of reality. They are the Platonic truths that lie beyond the grubby data gathered by scientific instruments.

However, I would like to suggest the opposite interpretation: The continuum differential equations of physics, including those of quantum physics, are only an approximate description of reality. The universe is fundamentally discrete, and only when that discreteness is to small to be noticed are we justified in using the continuum equations. Because most of our scientific interests lie on such scales, the continuity approximation leads to many useful results that agree beautifully with experiments. And so, on these scales, the universe appears orderly and predictable.

Even quantum mechanics is interpreted as operating in a spacetime continuum, and that is what leads us to think it is paradoxical. As we have seen, nonlocality such as seems to occur in quantum jumps occurs only when we assume a continuum.

On the ultimate quantum scale of Planck lengths and times, however, things are different. Space and time are discrete and motion is less predictable. At this scale, no evidence for a deeper Platonic realm that determines events is "shining through." Quite the contrary. Our differential equations and other idealized mathematical expressions appear simply as handy tools for making calculations that would otherwise require extensive numerical computation.

In Chapter 8, I mentioned that physicist-theologian Willem Drees agrees with me that neither the data nor the theories of modern physics and cosmology provide any rational basis for a transcendent world beyond matter.[48] Nonetheless he chooses to believe in such a world, admitting that his is a freely-chosen belief based on what he perceives as the human desire for justice and perfection. While I cannot bring myself to worship a hypothesis, I have no wish to disparage those who do. I simply ask that they not assume that science, in its current state, provides any buttress for their belief in a Platonic reality, whether it be mathematical forms or a more traditional deity.

The Me Decade

A decade ago, Fritjof Capra, Marilyn Ferguson, Gary Zukov, and others had predicted that the 1980s would be a revolutionary time "because the whole structure of our society does not correspond with the world-view of emerging scientific thought."[49] They blamed classical physics for all the ills of society and saw the new physics, especially quantum mechanics, as a savior.

In her 1990 book, *The Quantum Self,* Danah Zohar asserted that "Cartesian philosophy wrenched human beings from their familiar social and religious context and thrust us headlong into . . . our I-centered culture, a culture dominated by egocentricity."[50] The new holistic physics was supposed to teach people to be less selfish, to recognize that they are part of a greater whole and to work cooperatively for the benefit of everyone.

Notwithstanding, as I write in 1995 I can perceive no great holistic revolution actually having taken place in the decade past. The facts indicate the contrary. The 1980s have been characterized, in America anyway, as the "Me Decade." Far from recognizing that we are each an inseparable part of the whole, and everyone pitching in to make the world a better place for its inhabitants, life in the 1980s was characterized by an unprecedented level of individual self absorption. And the 1990s so far show no sign of a change in this focus on self, as every element of our society is geared to provide maximal short-term self gratification for its members and those who fail to be gratified view themselves as victims.

Now some will argue that the ever-increasing fixation with self only reinforces the need for a holistic philosophy like that of Capra, Ferguson, and Zohar. They will say the problem is that holistic philosophy simply has not yet taken hold. Disagreeing, I lay no small portion of the blame for current excessive self absorption at the feet of the new mysticism. Anyone listening to New Age gurus, and modern Christian preachers cannot miss the emphasis on the individual finding easy gratification - never sacrifice and selfless labor for a better world. It's the perfect philosophy for the spoiled brat of any age, all decked out in the latest fashion, who loves to talk about solving the problems of the world but has no intention to sweat a drop in achieving this noble goal.

Reductionist classical physics does not make people egoists. People were egoists long before classical physics. In fact, classical physics has nothing to say about humans except that they are material objects like rocks and trees and everything else, made of nothing more than the same atoms - just more cleverly organized by the impersonal forces of self-organization and evolution. This is hardly a philosophical basis for narcissism.

The new quantum holism, on the other hand, feeds our delusions of personal importance. It tells us that we are part of an immortal cosmic mind with the power to perform miracles and, as actress Shirley MacLaine has said, to make our own reality. Who needs God when we, ourselves, are God? Thoughts of our participation in cosmic consciousness inflate our egos to the point where we can ignore our imperfections, excuse our short-comings, and forget our mortality.

The modern versions of traditional religions also feed on this desire. Where once Christian preachers shouted hell-fire and brimstone from the pulpit, their successors in the very same sects now present the soothing message that we are all perfect, worthy, and destined for infinite happiness. The only sacrifice required is a regular check. Then Jesus will provide all.

As with traditional religions, New Age Christianity and other modern religions mainly provide a means for escaping reality. In the United States where self gratification has reached heights never dreamed of in ancient Rome, where self esteem is more important than being able to read, and where self help requires no more effort than putting on a cassette, the myth of quantum consciousness is just what the therapist ordered.

Quantum consciousness is a grossly misapplied version of ancient Hindu and Buddhist philosophy, which were deeply based on the notion that only by the complete rejection of self can one find inner peace in this world of suffering and hopelessness. Capra and his colleagues say they are building a modern face on ancient Eastern philosophy, but they are rather covering a noble edifice with graffiti. Where they see similarities between the new and the old mysticisms, I see only contrasts. Where they promote the new mythology as an antidote for self absorption, I assert it is a drug that induces self delusion. And while they blame rational science for the ills of the world, I hold rational science as a source of genuine hope, if only we and our successors have the wisdom to use it properly.

Notes

1. Crick 1994, p. 3.

2. Reports of apparent superluminal effects are often reported in the literature, in astronomical observations and in certain quantum experiments. However, these are all currently explained within conventional theory and cannot be used as evidence for the nonlocality expected from hidden variables theories.

3. Gould 1989, 1994.

4. Penrose 1989.

5. Penrose 1994.

6. Penrose 1994, p. 12.

7. Stenger 1990.

8. Penrose 1994, p. 202.

9. Searle 1980, 1992.

10. Edelman 1992, pp. 228-252.

11. Eddington 1958, pp. 333-334.

12. Gödel 1931.

13. Penrose 1989, p. 110.

14. Turing, 1937.

15. Church 1941.

16. For an excellent discussion, see Pagels 1989, pp. 294-296.

17. Penrose 1994, p. 51.

18. For a readable and thorough history of mathematics that goes from primitive counting to modern-day disputes, see Barrow 1992.

19. Penrose 1989, p. 112.

20. Davies 1992, p. 226.

21. Wilber 1984.

22. Wilber 1984, p. 5.

23. Armstrong 1993.

24. Stenger 1990.

25. *Behavioral and Brain Sciences* 1990, 13, pp. 643-705.

26. McCullough, Daryl 1995. Electronically-disseminated article from *Psyche*.

27. While it is possible to write down mathematically deterministic equations that do not have computationally tractable solutions, these have no value in science unless they produce useful numerical results. As usual, I am speaking here in pragmatic, scientific terms that may not satisfy the more purist-minded mathematician or philosopher.

28. Siegelmann 1995.

29. The possibilities of quantum computers is discussed in Deutsch 1985 and Feynman 1986b.

30. Zadeh 1965, Kosko 1994, Aminzadeh 1994.

31. Kosko 1994.

32. Popper and Eccles 1977, Eccles 1986, 1990.

33. Hameroff 1994, 1996.

34. Stapp 1993, p. 42.

35. Herbert 1993, p. 253.

36. Herbert 1993, p. 254; Squires 1990, p. 222.

37. Hameroff 1994, 1996; Penrose 1994, pp. 357-377.

38. Stapp 1993, p. 25.

39. Herbert 1993, p. 5.

40. Squires 1990, p. 229.

41. Squires 1990, p. 201.

42. Albert 1992.

43. Penrose 1989, p. 446.

44. Dennett 1991.

45. Edelman 1992.

46. Crick 1994.

47. Carley 1994.

48. Drees 1990.

49. As quoted in Ferguson 1980, p. 145.

50. Zohar 1990, p. 18.