PART ONE

THE QUANTUM BRAIN

INTRODUCTION

THE QUANTUM CRISIS

Our imagination is stretched to the utmost, not, as in fiction, to imagine things which are not really there, but just to comprehend those things which are there.
—Richard P. Feynman, *The Character of Physical Law* (1999)

This book is the story of a revolution that will transform our world and ourselves, one that already has drawn together neurobiologists, psychiatrists, computer scientists, physicists, and mathematicians in an unprecedented competition coordinated more by sheer excitement than by plan. The competition has two interdigitating goals: to achieve an ever more precise understanding of—hence control over—the human brain and to create ever more powerful synthetic brains. We are now approaching both goals with increasing speed, as the race to reach one goal supercharges the race toward the other. We can now see more clearly that both competitions ultimately lead us into the mysterious world of *quantum mechanics*.

When the dust settles, this revolution will, of course, bring about huge advances in science and technology. Scientists at the Massachusetts Institute of Technology and elsewhere, for example, are already planning for a forthcoming Internet that functions as a single, worldwide quantum computer. But the ideas that allow for such a technology represent a revolution in our understanding of ourselves, of life in general, even of God.

ENLIGHTENMENT

Our search to understand the brain has proceeded as has all scientific thought since the Age of Enlightenment: It presumes that there is nothing in the brain (indeed, nothing anywhere in the universe) that is more than *machine*. Neither brain nor mind is anything spiritual or insubstantial; there exists in man no soul, only a collection of physical objects affecting each other via impersonal forces. The unfolding states of these objects, however complicated, are completely determined by whatever states they were in previously: universal billiards without players, payoff, points—or point.

Set in motion once for all time at the Big Bang, particles that later happen to comprise a human brain have no freedom of action whatsoever, neither individually nor as an ensemble. That we think of ourselves as "free," as having "minds" capable of "choosing," indeed, that we even *think we think*: illusion all. What we like to call "will" is at most the inevitable by-product of mechanical interactions of the brain's parts. Illusory "mind" can influence neither what the brain does nor the bodily actions the brain sets into motion.

Poets, mystics, philosophers, and theologians have always insisted that this game of universal billiards has both players and purpose—and their followers have ever fought over who and what these are. But ever since the Enlightenment, science has argued that it is both impossible and unnecessary to know whether the opening break was that of a cosmic Minnesota Fats of incomparable foresight or of a merely comic amateur. In either case, the cue stick lies long abandoned; the player long gone from the shot, the table, the game. The pool hall itself is empty, though the neon lights burn on. In the words of Harvard astronomer Margaret Geller: "Why should [the universe] have a point? What point? It's just a physical system, what point is there?"[1]

For all the millennia that human beings looked at the universe as guided, purposeful, and pregnant with meaning, its operations remained mysterious. But once science arose, the universe swiftly began to yield its secrets. By shifting so wholeheartedly to this point of view that not even life, not even human life, is exempted, science has found itself able to break open even seemingly impenetrable mysteries of mind: learning, intelligence, intuition—all of these can now be extensively understood in wholly mechanical terms. What's more, they are being mimicked by man-made machines. More powerfully than has any prior scientific discovery, the unlocking of the brain seems to confirm the scientists' hypothesis that everything—the mind of man included—is machine.

Steven Weinberg, winner of the 1979 Nobel Prize in physics and an eloquent spokesman for the machine point of view, put it this way: "The more the universe seems comprehensible, the more it seems pointless."[2] And more: "It would be wonderful to find in the laws of nature a plan prepared by a concerned creator in which human beings played some special role. I find sadness in doubting that we will . . . And it does not seem to me to be helpful to identify the laws of nature as Einstein did with some sort of remote and disinterested God. The more we refine our understanding of God to make the concept plausible, the more it [too] seems pointless."[3]

The idea that the entire universe is nothing more than a "physical system"—that is, a machine—unfolding mechanically according to rigid and immutable laws began as the radical heresy of a few brave minds. With this idea as their starting point, they and their followers began to experience an uninterrupted string of successes. There is not a single working medical device or treatment, not a vehicle, not a communications technology, not an industry that isn't based on this assumption. Between the age of Galileo and the end of the twentieth century, the once-radical heresy had become a worldview shared by billions (whether aware or not). So far has this transformation gone that here in America, for instance, where it was once a requirement that a professor in any department in any reputable university be a "man of God," it is now rather an embarrassment should he admit to taking seriously such a thing. The renowned evolutionary zoologist, Richard Dawkins, maintains that anyone who believes in a creator God is simply "scientifically illiterate." By the end of the nineteenth century, scientists believed they had uncovered almost all of the fundamental laws of physics. These laws were all purely mechanical, and out of their mechanical interactions (however complicated-seeming and difficult, in practice, to track these may be) arises every phenomenon we experience at every scale. Living matter itself was understood to be nothing more than an especially complicated factory of molecular machinery.

Needless to say, there were (and are) a great many people who found this vision of reality a horribly bleak one. Most understood little enough about the subtleties of the mechanistic point of view, and of scientific method, to allow them to dismiss it without ever seriously experiencing the power of its claims. But there were a few who did indeed understand its power and hoped that eventually it would somehow be proven wrong. They hoped, in other words, that one day scientists themselves might discover a fundamental law of the universe that was *not* wholly mechanical but in some sense "free." These hopes were rekindled with the emergence of the strange theory of *quantum mechanics*.

QUANTUM LONGINGS

While it is true that at the turn of the last century almost every fundamental physical phenomenon seemed understood, three did resist explanation by the mechanical view of nature. Of course, none of them seemed to have any larger implications about the nature of man, of free will, of life, of God. And to the man in the street they were utterly uninteresting:

- Why does a radioactive nucleus spit out an alpha particle *now* but not *then,* and completely at random? (The mechanical view predicts that there ought to be some kind of regular, internal clock that orders its departure, but there is none.)
- If you heat up any completely black object—like a bowling ball—why is the heat it radiates back at you invisible, and why is it always *heat*, that is, "infrared radiation," and always in the exact same distribution of infrared "colors"? (The mechanical view predicts that the hotter the bowling ball, the more the radiated energy should be as visible light, starting with red, running through the rainbow, and then into the ultraviolet. Note: We're not talking about making the ball so hot that it glows by itself!)
- If you shine light on metal, it will eject electrons—"the photoelectric effect." If the color is right for the metal, *or more toward the blue*, an electron will always be spit out *at once,* no matter how faint the light. But if the color of the light is more toward the red, it doesn't matter if the light

has the intensity of an industrial laser—an electron will *never* be spit out. Why? (The mechanical view predicts that as long as you shine enough light—and there ought to be some minimum—it shouldn't matter what the color is or how intense is the beam.)

These do not seem like earth-shaking quandaries. But when scientists finally did figure out the answers, most of them received a tremendous shock and some had an equally tremendous hope. For the theory that solved these dilemmas—*quantum mechanics*—gave the following Delphic answers:

Nothing at all in the physical universe "causes" an alpha particle to jump out of its nucleus when it does. It just does so, "whenever it wishes." Not only that, it gets out in spite of the fact that the barrier keeping it in is too high for it to get out at all. Were the world really as tidy as scientists had thought, the alpha particle ought no more *ever* be able to get out of its nucleus than could a prisoner in a cell on Alcatraz instantly appear in San Francisco.

Hot, black bodies are black because energy comes in discrete units. This doesn't sound weird, but it's akin to discovering that time only comes in units of hours so you couldn't ever experience or measure time passing during an hour; it would just jump from one hour to next.

A beam of the right color light, no matter how faint, instantly generates electricity in a metal because, *even if the light is spread out like energy, it is at the same time a billiard ball–like particle that knocks an electron out of its orbit.* But if the color is wrong and the energy of the light is too low, it doesn't matter how many particles you throw at the metal, none of the electrons will budge—like throwing thousands of Ping-Pong balls at a bowling ball stuck in a rut.

In the century since it first appeared, quantum theory has created many new dilemmas, solved those dilemmas as well, and all in all proven itself the most successful theory in the history of science. In doing so, it has demonstrated that at its foundation, matter itself does not behave like a machine at all. The very mechanical premises upon which science has been built may be overturned by science itself. This has given some hope that we may find in quantum theory an exit from the dead-end trap of a world that "has precisely the properties we should expect if there is, at bottom, no design, no purpose, no evil and no good, nothing but blind, pitiless indifference," in the words of the eminent evolutionist Richard Dawkins.

Some of these quantum exits take the strange phenomena found at the quantum, subatomic scale and apply them wholesale to human life because of the analogies one can make between, for example, the freedom of choice we believe that we, as people, have and the "freedom of choice" that electrons apparently have. Most serious scientists reject such analogizing because they know enough about how quantum mechanical effects "scale upward" to be convinced that any and all quantum weirdness is long gone by the time we are dealing with aggregates of gazillions of particles large enough to form people.

But as modern biological science has penetrated down into the *subcellular* levels of living matter, and in particular those that constitute the brain, it has indeed begun to encounter the eerie quantum effects that have confounded physicists for a century. These effects are not analogies, they are real, and, as we will see, it is only by considering them that we can begin to understand the building blocks of life. That this is so is not yet widely known to most biologists, but it soon will be. And it will have a dramatic effect on both science and on scientists.

At the subcellular level, matter itself actually looks and behaves (in the words of one physicist) "more like a thought" than like the cogs of a machine. *Nothing in the world that causes the particle to jump,* discovered the first quantum mechanics. But the first premise of science is that *everything happens solely as a result of causes in the world.* "If we are going to stick to this dammed quantum-jumping," complained one of its founders, "then I regret that I ever had anything to do with quantum theory."[4]

Furthermore, if subatomic particles can freely choose to come and go as they please, then perhaps old-fashioned claims as to our own nonmechanical nature aren't so archaic after all: Suddenly, the machinery of brain might prove the illusion, mind and will a more foundational reality. A number of the founders of quantum mechanics wondered out loud whether the ancient mystics might not be right after all: Perhaps there is a Player. Standing apart from the mere "physical system," he everywhere spins the shots, making everything happen *this* way rather than *that.* Wolfgang Pauli thought so: Tongue not wholly in cheek, he simply referred to the so-called exclusion principle, a cornerstone of modern physics and chemistry, as "God."

It turns out, however, that the amount of absolute "freedom" individually available to the bits and pieces of the universe is unbelievably tiny. It amounts to much only on the scale of atomic and subatomic particles. At any scale large enough to be of concern to human beings (e.g., for stuff the size of viruses), the net effect of all that freedom is zero—it just cancels out. Electrons may jump from here to there for no reason whatsoever, but planets don't; nor boulders; nor grains of sand; nor we.

But now the revolution: It appears possible that instead of averaging freedom away as usual, *the human brain,* itself a machine, has nonetheless evolved a unique structure that harnesses subatomic "choice," concentrates it, and amplifies it upward, scale by scale, taking advantage, as we will see, of the strange facts of "chaos." Of all things, it's the machine in our head that lets us transcend our own mechanicality.

Our brains are, if you will, "quantum computers." But they are not of the sort now making headlines. Subtle quantum effects in the brain afford us a capacity we would not otherwise have, yet to make maximum use of such effects our natural brains are now designing even better synthetic ones. These employ quantum principles directly, not, as in the human brain, in subtle and nearly invisible fashion. Some of them will be set free to evolve themselves in Darwinian fashion, hardware and all. But if quantum processes are the source within the human brain of genuine thought—as also of genuine will, intention, and choice—then the quantum computers we are on the verge of designing (or whose evolution we are at least facilitating) may turn themselves into genuine sentient beings. They may have as much intelligence as we have, quite possibly more: There are severe limits to how much quantum weirdness the human brain may employ (and of which sort—a distinction we'll make clear); the limits on how much a synthetic brain might employ are far less severe. Vast, synthetic, self-evolving, superintelligent, and completely sentient computers must surely sound like pure science fiction, but they are not. Nor are they from some far distant future.

Furthermore, in the human brain, the amplification of quantum freedom happens via means that preserve the appearance, at our day-to-day scale, that we, and our universe, are completely mechanical. All this is terribly confounding to philosophers who seek to understand the world, and human life, in terms with which they are already familiar. But to really understand where science is leading us may well require a great deal more intellectual discipline and envelope-pushing than rock-ribbed reductionists, tradition-minded theists, or New-Age hand-wavers are comfortable with: *"Our imagination is stretched to the utmost, not, as in fiction, to imagine things which are not really there, but just to comprehend those things which* are *there,"* in the words of Richard Feynman, the renowned theoretical physicist.[5] Many scientists speak of a "crisis" brought about by the implications of quantum mechanics and look for something cleaner, more truly a "mechanics," to replace it and to restore the austere reductionism of the Enlightenment. Not a few see confirmation of ancient religious notions. But there are some who see something wholly new, fraught with both fantastic opportunity and terrible risk. If human nature remains true to its history, we may expect both the risk and the opportunity to be realized, with much gain and much loss. In any event, our understanding of who we are, where we came from, our standing in the greater scheme of things, and where we're going, all looks soon to suffer a dramatic change.