3. HOW YOUR FREE CHOICES INFLUENCE YOUR BRAIN.

From the time of Isaac Newton to the beginning of the twentieth century science relegated consciousness to the role of passive viewer: our thoughts, ideas, and feelings were treated as impotent bystanders to a march of events controlled wholly by contact interactions between tiny mechanical elements. Conscious experiences, insofar as they had any influences at all on what happens in the world, were believed to be completely determined by the motions of miniscule entities, and the behaviors of these minute parts were assumed to be fixed by laws that acted exclusively at the microscopic level. Hence the *idea-like* and *felt* realities that make up our streams of conscious thoughts were regarded as at most redundant, and were denied fundamental status in the basic theory of nature.

The revolutionary move of the founders of quantum mechanics was to bring conscious human experiences into the basic theory of physics in a fundamental way. In the words of Niels Bohr the key innovation was to recognize that "in the drama of existence we ourselves are both actors and spectators." [Bohr, Essays 1958/1962 on Atomic Physics and Human Knowledge]. After two hundred years of neglect, our thoughts were suddenly thrust into the limelight. This was an astonishing reversal of precedent because the enormous successes of the prior physics were due in large measure to the policy of keeping idea-like qualities out.

What sort of crises could have forced scientists to this wholesale revision of their idea of the role of mind in their description of Nature? The answer is the discovery and integration into physics of the "quantum of action." This property of matter was discovered and measured in 1900 by Max Planck, and its measured value is called "Planck's Constant." It is one of three absolute numbers that are built into the fundamental fabric of the physical universe. The other two are the gravitational constant, which fixes the strength of the force that pulls every bit of matter in the universe toward every other bit, and the speed of light, which controls the response of every particle to this force, and to every other force. The integration into physics of each of these three basic quantities generated a monumental shift in our conception of nature.

Isaac Newton discovered the gravitational constant, which linked our understanding of celestial and terrestrial dynamics. It connected the motions of the planets and their moons to the trajectories of cannon balls here on earth, and to the rising and falling of the tides. Insofar as his laws are complete the *entire physical universe* is governed by mathematical equations that link every bit of matter to every other bit, and that moreover fix the complete course of history for all times from conditions prevailing in the primordial past.

Einstein recognized that the "speed of light" is not just the rate of propagation of some special kind of wave-like disturbance, namely "light". It is rather a fundamental number that enters into the equations of motion of every kind of material substance, and that, among other things, prevents any piece of matter from traveling faster than this universal limiting value. Like Newton's gravitational constant it is a number that enters ubiquitously into the basic structure of Nature. But important as the effects of these two quantities are, they are, in terms of profundity, like child's play compared to the consequences of Planck's discovery.

Planck's "quantum of action" revealed itself first in the study of light, or electromagnetic radiation. The radiant energy emerging from a tiny hole in a heated hollow container can be decomposed into its various frequency components. Classical nineteenth century physics gave a clean prediction about how that energy should be distributed among the frequencies, but the empirical facts did not fit that theory. Eventually, Planck discovered that the correct formula could be obtained by assuming that the energy was concentrated in finite packets, with the amount of energy in each such unit being directly proportional to the frequency of the radiation that was carrying it. The ratio of energy to frequency is called "Planck's constant". Its value is extremely small on the scale of normal human activity, but becomes significant when we come to the behavior of the atomic particles and fields out of which our bodies, brains, and all large physical objects are made.

It took twenty-five years for Planck's "quantum of action" to be integrated coherently into physics. During that interval, from 1900 to 1925, many experiments were performed on atomic particles and it was repeatedly found that the classical laws did not work: they gave well defined predictions that were contradicted by the empirical facts. And it was evident that all of these departures of fact from theory were linked to Planck's constant.

Heisenberg finally discovered in 1925 the completely amazing and wholly unprecedented solution to the puzzle of the failure of the classical laws: the quantities that classical physical theory was based upon, and which were thought to be numbers, *are not numbers at all*. Ordinary numbers, such as 2 and 3, have the property that the product of any two of them does not depend on the order of the factors: 2 times 3 is the same as 3 times 2. But Heisenberg discovered that one could get the correct answers out of the old classical laws if one decreed that the *order in which one multiplies* certain quantities matters!

This "solution" may sound absurd or insane. But mathematicians had already discovered that completely coherent and logically consistent mathematical structures exist in which the order in which one multiplies quantities matters. Ordinary numbers are just a very special case in which A times B happens to be the same as B times A. There is no logical reason why Nature should not exploit the more general case, and there is no compelling reason why our physical theories must be based exclusively on ordinary numbers. Quantum theory exploits the more general logical possibility.

An example may be helpful. In classical physics the center-point of each object has, at each instant, a well defined location, which can be specified by giving its three coordinates *(x, y, z)* relative to some coordinate system. For example, the location of a spider dangling in a room can be specified by letting *z* be its distance from the floor, and letting *x* and y be its distances from two intersecting walls. Similarly, the *velocity* of that dangling spider, as she drops to the floor, blown by a gust of wind, can be specified by giving *the rate of change* of these three coordinates (x, y, z). If each of these three rates of change, which together specify the velocity, are multiplied by the weight (=mass) of the spider, then one gets three numbers, say (p, q, r), that define the "momentum" of the spider.

Now in classical mechanics the symbols x and p described above both represent *numbers*: the symbol *x* represents the distance of the spider from the first wall, measured in some appropriate units, say inches; and the symbol p likewise represents some *number* connected to the velocity and weight of the spider. Because *x* and *p* both represent just ordinary *numbers*, the product x times p is the same as p times x, as we all learned in school. But Heisenberg's analysis showed that in order to make the formulas of classical physics describe quantum phenomena, x times p must be different from p times x. Moreover, he found that the difference between x times p and p times x must be Planck's constant. [Actually, the difference is Planck's constant multiplied by the imaginary unit *i,* which is a number such that *i* times *i* is minus one.] Thus quantum theory was born by recognizing, or declaring, that the symbols used in classical physical theory to represent ordinary numbers actually represented mathematical objects such that their ordering in a product is important. The procedure of creating the mathematical structure of quantum mechanics from classical physics by replacing ordinary numbers by these more complex objects is called "quantization."

This step of replacing the numbers that specify where a particle is, and how fast it is moving, by mathematical quantities that violate the simple laws of arithmetic may strike you---if this is the first you've heard about it---as a giant step in the wrong direction. You might mutter that scientists should try to make things simpler, rather than abandoning one of the things we really know for sure, namely that the order in which one multiplies factors does not matter. But against that intuition you need to bear in mind that this change works beautifully in practice. More importantly, it disrupts old laws of physics in just such a way as to bring your conscious thoughts into physics as causal agents with “free choices”: choices that can influence your behavior but are controlled neither by the deterministic laws that fix the motions of the elementary particles, nor by any other known law. This revision of the physics severs in one stroke the logical chain that had hobbled philosophy for two and a half centuries. It converts the world of physics from a collection of tiny material particle and local fields to a mathematical structure that represents *our knowledge* and creates *tendencies for future knowings to occur.* Matter has thus been banished from the world, and replaced by idea-like realities.

This radical revision in our conception of the world might appear to be a consequence of injecting so much craziness into physics---by abandoning the time-honored laws of arithmetic---that by now any wild idea seems reasonable. But von Neumann has made the new mathematics quite rigorous, and these revolutionary philosophical consequences flow naturally from it.

The idea that the product AB of two quantities, A and B, is different from BA may seem weird, or impossible. But this property is completely understandable if A and B are "matrices." Quantum mechanics is sometimes called "matrix mechanics" because it can be understood as a consequence of replacing ordinary numbers by matrices. But what are "matrices?"

An N-by-N matrix is a square array of numbers arranged in N rows each having N numbers. Or one can think of it as consisting of N columns each having N numbers. So it is a square array of numbers with N rows and N columns. If M is a matrix then mathematicians label the individual number that lies in row number i and column number j by M(i,j). Thus M(2,3) is the number that lies in the second row and the third column of the matrix M. If you abhor math you can ignore these details, but you do need to know that matrices are well defined mathematical objects: there is no vagueness about them. Moreover, the product C=AB is well defined. The rule is C(i,j)=A(i,k)B(k,j) summed over all N values of k. One can easily verify, already for N=2, that AB is usually different from BA.

I shall not use these formulas in any explicit way. But it is important to recognize that AB and BA are both well defined, and are generally different.

In quantum theory each physical system, from an individual electron, to a small device, to a human brain, and to still larger systems, is represented by an N-by-N square matrix S called a density matrix. The number N is generally infinite, but that is not an insuperable problem. The important feature of matrix mechanics is that, according to this mathematical description, no object, large or small, has a well defined location and velocity: every object, and combination of objects, is represented by a smeared out cloud, or wave.

This expanding cloudlike character of physical systems produces a serious problem when it comes to relating the mathematical description given by quantum theory to human experience. Each of us experiences any visible physical object as having a fairly well defined location: its center is not experienced as being ambiguously smeared out over several centimeters, or perhaps even meters or kilometers. In classical physics this experiencing of definite locations is easy to understand. Each small object has a well defined position at each moment, and one can imagine bouncing light off the object, then following the reflected light from the object to some particular small region of the retina. The excitation of the nerves in this portion of the retina could cause the brain to evolve into a state that would depend upon where the light hit the retina. That location would depend upon where the object was located. Hence the ensuing visual experience could easily depend upon where the object was located: the person could "see" where the object is situated.

But if one tries to follow the same reasoning in quantum theory then the cloudlike character of an object causes a problem: it would lead to a corresponding cloudlike state of the brain. The brain would evolve into a smeared-out structure in which all of the possible locations of the object are represented: no single location of the object would be singled out and distinguished from the others. Thus the experience of the observer would contain components corresponding to a whole set of different locations of the object, contrary to the empirical facts.

The basic problem, therefore, is that the replacement of simple numbers by matrices---i.e., by huge arrays of numbers---tends to smear everything out, including the states of the brains of the observers. Consequentially, it would seem that, according to the theory, each object should appear to be everywhere, rather than somewhere. This disparity between the raw theory and ordinary experience is the fundamental problem that was resolved by the founders of quantum theory by bringing the actions of human experimenter into the dynamics in an essential way.

In both the original Copenhagen quantum theory and von Neumann's reformulation of it the dynamical rules involve an effect of an action by a human agent upon the state of an observed physical system.

But this agent is treated differently in these two versions. In particular, “The Observer" in the Copenhagen version differs greatly from what is normally meant by this term: it involves an extension of the human observer outside his physical body.

Bohr mentioned several times the example of a man with a cane: if he holds the cane loosely he feels himself to extend only to his hand. But if he grips the cane firmly then the outer world seems to begin at the tip of his probing cane. Correspondingly, "The Observer" in Copenhagen quantum theory includes not only the body and mind of the experimenter himself, but also the measuring devices that he uses to probe some “observed system” that lies outside of his extended "self". Thus nature is imagined to be cleaved into two parts, which are described in different ways. The outer "observed system" is described in terms of quantum mathematics, whereas the inner "observing system" is described in terms of experiential facts. Because Copenhagen quantum theory treats the measuring instruments as part of the observer these devices are described in terms of our experiences of them, not in terms of their atomic constituents. Thus the dynamics becomes an interaction between this extended observer, which is described in experiential terms, and the reality that he is probing, which is described by an evolving matrix. The laws of physics must therefore be expanded from laws that govern simply the physical world alone to laws governing the dynamical interplay between an agent and an external-to-himself system that he is probing.

But how does one enlarge physical theory to encompass a dynamical interplay between an experientially/psychologically described agent and the physically/mathematically described object he is studying?

The solution arises from the apparently innocent fact that in order to extract precise information from nature the experimenter has to put in place a measuring device. Thus his action results in the coming into being of some particular experimental set-up that probes nature in some particular way. The essential feature of these devices is that they never give answers questions of the form “What is the value of X?” where X ranges over a continuous set of values. Rather they answer questions with a discrete set of possible answers: a Geiger counter either gives an audible click or it doesn’t.

Basically, the intentional act of the experimenter is to cause the world either to return a certain recognizable response, or fail to return that response. Thus the experimenter poses, or puts to nature, a question that has a discrete answer, ‘Yes’ or ‘No’. But discrete answers cannot be produced by the Process II derived from quantization of the classical laws. For that process is basically continuous in both time and space. Thus the posing and answering of the specific question involves a second natural process, and the theory is not complete until it is specified.

Copenhagen quantum theory is thus formulated in a realistic and practical way. It is structured around the activities of human agents, who can freely elect to probe nature in any one of many possible ways. Bohr emphasized the freedom of the experimenters in passages such as:

"The freedom of experimentation, presupposed in
classical physics, is of course retained and corresponds
to the free choice of experimental arrangement for which
the mathematical structure of the quantum mechanical
formalism offers the appropriate latitude."

This freedom of the agent stems from the fact that in Copenhagen quantum theory the human experimenter stands outside the system to which the quantum laws are applied. Those quantum laws are the only precise laws of nature recognized by that theory. Thus, according to the Copenhagen philosophy, there are no presently known laws that govern the choices made by the agent/experimenter/observer about how the observed system is to be probed. This choice is, in this very specific sense, a “free choice.”

The Copenhagen separation of the dynamically unified physical world into two differently described parts, the observing system and the observed system, is pragmatically useful, but the origin of much dissatisfaction among those who seek a rationally and dynamically coherent understanding of what is actually going on. Von Neumann evaded this unnatural bifurcation of the physical world by devising a rigorous formulation of quantum theory that treats the entire physical world, including the bodies and brain of the human agents, as belonging to the physical part of reality that is described by the quantum mathematics. Then the brain of the agent becomes the observed system, the measuring device, and the physical part of observer. However, the free choice of which question is put to nature must still be made, and must still be made by some process other than the dynamical process that arises from the quantization of the classical laws.

This process of observation is of such essential importance to quantum theory that von Neumann calls it Process I. He calls the quantized version of the classical dynamical process Process II. Thus the quantum dynamics involves *two* processes, only one of which is analogous to the local deterministic process of classical physics. This latter process, applied to the brain, is a “bottom up” process, in the sense that, like the dynamical process of classical physics, it is expressed in terms of contact interactions between elementary particles and fields (even though these quantities are now matrices.) Process II, like its classical analog, is also deterministic. However, the other process, Process I, is “top down.” It involves a volitionally controlled probing action that involves the experience of an agent and its physical correlate: a high-level activity of his brain.

Notice that the relationship between the mind and the brain of the agent is specified in von Neumann quantum theory not by some abstract metaphysical principle of mind-brain connection that is *added onto* the dynamical theory. This relationship is specified rather by an essential *dynamical* process of the physical theory itself. This dynamical process allows the conscious intentional action of the agent to have *a causal influence upon his brain*, which in turn causes activities that act back on his ongoing stream of conscious thoughts. This chain of causal connections allows a correspondence between the experiential and physical domains to be established *empirically*: the infant, child, and adult all learn, by experience, which of their intentional feelings tend to produce which experiential feedbacks. Thus the relationship between these two disparate aspects of the agent need not be specified by some mysterious metaphysical principle that connects two logically and dynamically independent realms, as is required in Cartesian dualism. It can be, and surely is, established by trial and error learning.

Von Neumann pushed the physical world out to include the brain of the agent, but gave no prescription for specifying how the choice associated with Process I is made. Thus at this stage of the developments of physical theory the choice on the part of the agent that is needed to specify which of the possible Process I events actually occurs (i.e., which of the dynamically possible actions is actually performed by the agent) remains a “free choice,” in the specific sense that it is not fixed either statistically or deterministically by the laws of contemporary physical theory.

The essential point of this book has now been made. According to classical mechanics, everything that happens in the physical world is determined by a single *bottom up* local deterministic physical process, and we ourselves are, consequently, robotic automata. This fact can be disguised by noting that high-level entities such as wheels, pistons can cause things, and exercise control over low-level events. But a robot is no less robotic by virtue of having big or complex parts. The bottom up process controls everything, and the various entailed top down processes are merely partial and approximate re-expressions of the bottom up process. But according to quantum theory, at least in its von Neumann form, the human agents are governed by *two* processes. One of them is bottom up, but the other is a genuine top down process. It is not controlled or determined by the bottom up process, as far as we know, and it involves both our thoughts and their large-scale correlates in the brain.

The Process-I connection between intentional thoughts and the physical brain is the foundation of human personhood. Hence it must be described here. Physicists have their own relevant jargon for describing Process I, and rather than giving vague restatements I shall, instead, describe the process in the language used by the physicists, and explain the meaning of the terms used.

Quantum theory, as already noted, replaces numbers by matrices. This complexity permits the entry of new conceptions that escape the narrow bounds of what classical physics allows. This shift to matrix mechanics is a wonderful boon, for it allows us to reconcile our intuitive idea of what we are with the basic laws of science.

The complexity of these huge infinite-dimensional matrices actually engenders a certain conceptual simplicity. The entire brain of the agent is represented by an infinite-dimensional matrix. Hence, conceptually, the same matrix idea applies just as well to a whole brain as to a single coordinate x of single particle.

Suppose the infinite-dimensional matrix that represents the entire brain of the agent (or perhaps the portion of that brain that is associated with a conscious experience) is called S. Then the key question is: What happens to S when a Process I event occurs? This transformation constitutes the action of mind on brain.

This action involves “projection operators.” A matrix P is a projection operator if and only if PP = P: i.e., if P times P is P itself. There are exactly two ordinary numbers that have this property, zero and one: zero times zero is zero, and one times one is one. No other numbers have this property, But for any number N greater than 1 here are an infinite number of matrices P such that P is an N dimensional square matrix, and P times P is P.

The von Neumann Process I describes the encoding in the brain of an agent of the consequence of an intentional act by that agent. This encoding is specified by a projection operator P, which acts as a whole on the entire state S of the brain. The action of Process I is this: If the symbol “I” stands for the matrix that has one (unity) in every diagonal location (i.e., I(i,i) = 1 for every value of i) and zero in every other location (i.e., I(i,j) = 0 for i different from j) then the effect of Process I is to replace S by S’= PSP + (I-P)S(I-P).

The two terms PSP and (I-P)S(I-P) are called the “branches” of the new state S’. The branches PSP and (I-P)S(I-P) correspond to the experiential answers ‘Yes’ and ‘No’, respectively, to the probing question. Thus Process I specifies the mind-brain connection.

I shall explain in some detail the consequences of this formula, but here merely emphasize that Process I is the dynamical representation in the physical world of an intentional action on the part of the agent, and that this action involves a choice on the part of the agent that is “free” in the specific sense that it is not fixed by any *known* law of nature.