

PHYSICS IN NEUROSCIENCE

Classical Physics

Classical physics is a theory of nature that originated with the work of Isaac Newton in the seventeenth century and was advanced by the contributions of James Clerk Maxwell and Albert Einstein. Newton based his theory on the work of Johannes Kepler, who found that the planets appeared to move in accordance with a simple mathematical law, and in ways wholly determined by their spatial relationships to other objects. Those motions were apparently *independent of our human observations of them*.

Newton assumed that all physical objects were made of tiny miniaturized versions of the planets, which, like the planets, moved in accordance with simple mathematical laws, independently of whether we observed them or not. He found that he could explain the motions of the planets, and also the motions of large terrestrial objects and systems, such as cannon balls, falling apples, and the tides, by assuming that every tiny planet-like particle in the solar system attracted every other one with a force inversely proportional the square of the distance between them.

This force was an *instantaneous action at a distance*: it acted instantaneously, no matter how far apart the particles were located. This feature troubled Newton. He wrote to a friend “That one body should act upon another through the vacuum, without the mediation of anything else, by and through which their action and force may be conveyed from one to another, is to me so great an absurdity that I believe no man, who has in philosophical matters a competent faculty of thinking, can ever fall into it.” (Newton

1687: 634) Although Newton's philosophical persuasion on this point is clear, he nevertheless formulated his universal law of gravity without specifying how it was mediated.

Albert Einstein, building on the ideas of Maxwell, discovered a suitable mediating agent: a distortion of the structure of space-time itself. Einstein's contributions made classical physics into what is called a *local theory*: there is no action at a distance. All influences are transmitted essentially by contact interactions between tiny neighboring mathematically described "entities," and no influence propagates faster than the speed of light.

Classical physics is, moreover, *deterministic*: the interactions are such that the state of the physical world at any time is completely determined by the state at any earlier time. Consequently, according to classical theory, the complete history of the physical world *for all time* is mechanically fixed by contact interactions between tiny component parts, together with the initial condition of the primordial universe.

This result means that, according to classical physics, *you are a mechanical automaton*: your every physical action was pre-determined before you were born solely by mechanical interactions between tiny mindless entities. Your mental aspects are *causally redundant*: everything you do is completely determined by mechanical conditions alone, without reference to your thoughts, ideas, feelings, or intentions. Your intuitive feeling

that your mental intentions make a difference in what you do is, according to the principles of classical physics, a false and misleading illusion.

There are two possible ways within classical physics to understand this total incapacity of your mental side - your stream of consciousness - to make any difference at all in what you do. The first way is to consider your thoughts ideas, and feelings to be epiphenomenal by-products of the activity of your brain. Your mental side is then a causally impotent sideshow that *is produced*, or *caused*, by your brain, but that *produces* no reciprocal action back upon your brain. The second way is to contend that your mental aspects are the *very same things* as certain of motions of various tiny parts of your brain.

Problems with classical physics

William James (1890: 138) argued against the first possibility, epiphenomenal consciousness, by arguing that “*The particulars of the distribution of consciousness, so far as we know them, points to its being efficacious.*” He noted that consciousness seems to be “an organ, superadded to the other organs which maintain the animal in its struggle for existence; and the presumption of course is that it helps him in some way in this struggle, just as they do. But it cannot help him without being in some way efficacious and influencing the course of his bodily history.” James said that the study described in his book “will show us that consciousness is at all times primarily a *selecting agency*.” It is present when choices must be made between different possible courses of action. He further mentioned that “It is to my mind quite inconceivable that consciousness should have *nothing to do* with a business to which it so faithfully attends.”(1890: 136)

If consciousness has no effect upon the physical world then what keeps a person's mental world aligned with his physical situation: what keeps his pleasures in general alignment with actions that benefit him, and pains in general correspondence with things that damage him, if pleasure and pain have no effect at all upon his actions?

These liabilities of the notion of epiphenomenal consciousness lead most thinkers to turn to the alternative possibility that a person's stream of consciousness is *the very same thing* as some activity in his brain: consciousness is an "emergent property" of brains.

A huge philosophical literature has developed arguing for and against this idea. The primary argument against this "emergent-identity theory" position, *within a classical physics framework*, is that within classical physics the full description of nature is in terms of numbers assigned to tiny space-time regions, and there appears to be no way to understand or explain how to get from such a restricted conceptual structure, which involves such a small part of the world of experience, to the whole. How and why should that extremely limited conceptual structure, which arose basically from idealizing, by miniaturization, certain features of observed planetary motions, suffice to explain the totality of experience, with its pains, sorrows, hopes, colors, smells, and moral judgments? Why, given the known failure of classical physics at the fundamental level, should that richly endowed whole be explainable in terms of such a narrowly restricted part?

The core ideas of the arguments in favor of an identity-emergent theory of consciousness are illustrated by Roger Sperry's example of a "wheel." (Sperry, 1991.) A wheel obviously does something: it is causally efficacious; it carries the cart. It is also an *emergent property*: there is no mention of "wheelness" in the formulation of the laws of physics, and "wheelness" did not exist in the early universe; "wheelness" *emerges* only under certain special conditions. And the macroscopic wheel exercises "top-down" control of its tiny parts. All these properties are perfectly in line with classical physics, and with the idea that "a wheel is, precisely, a structure constructed out of its tiny atomic parts." So why not suppose "consciousness" to be, like "wheelness", an emergent property of its classically conceived tiny physical parts?

The reason that consciousness is not analogous to wheelness, within the context of classical physics, is that the properties that characterize wheelness are properties that are *entailed*, within the conceptual framework of classical physics, by properties specified in classical physics, whereas the properties that characterize consciousness, namely the way it feels, are not *entailed*, within the conceptual structure provided by classical physics, by the properties specified by classical physics.

This is the huge difference-in-principle that distinguishes consciousness from things that, according to classical physics, are constructible out of the particles that are postulated to exist by classical physics.

Given the state of motion of each of the tiny physical parts of a wheel, as it is conceived of in classical physics, the properties that characterize the wheel - e.g., its roundness, radius, center point, rate of rotation, etc.,---are specified within the conceptual framework provided by the principles of classical physics, which specify only geometric-type properties such as changing locations and shapes of conglomerations of particles, and numbers assigned to points in space. But given the state of motion of each tiny part of the brain, as it is conceived of in classical physics, the properties that characterize the stream of consciousness - the painfulness of the pain, the feeling of the anguish, or of the sorrow, or of the joy - are not specified, within the conceptual framework provided by the principles of classical physics. Thus it is possible, within that classical physics framework, to strip away those feelings without disturbing the physical descriptions of the motions of the tiny parts. One can, within the conceptual framework of classical physics, take away the consciousness without affecting the locations and motions of the tiny physical parts of the brain. But one cannot, within the conceptual framework provided by classical physics, take away the wheelness of the wheel without affecting the locations and motions of the tiny physical parts of a wheel.

Because one can, within the conceptual framework provided by classical physics, strip away the consciousness without affecting the physical behavior, one cannot rationally claim that the consciousness is the *cause* of the physical behavior, or is *causally efficacious* in the physical world. Thus the “identity theory” or “emergent property” strategy fails in its attempt to make consciousness efficacious, within the conceptual framework provided by classical physics. Moreover, the whole endeavor to base brain

theory on classical physics is undermined by the fact that the classical theory fails to work for phenomena that depend critically upon the properties of the atomic constituents of the behaving system, and brains are such systems: brain processes depend critically upon synaptic processes, which depend critically upon ionic processes that are highly dependent upon their quantum nature. This essential involvement of quantum effects will be discussed in later sections.

The Quantum Approach

Classical physics is *an approximation* to a more accurate theory - called quantum mechanics - and quantum mechanics makes mind efficacious. Quantum mechanics *explains* the causal effects of mental intentions upon physical systems: it explains how your mental effort can produce the brain events that cause your bodily actions. Thus quantum theory converts science's picture of you from that of a mechanical automaton to that of a mindful human person. Quantum theory also shows, explicitly, how the approximation that reduces quantum theory to classical physics completely eliminates all effects of your conscious thoughts upon your brain and body. Hence, from a physics point of view, trying to understand the mind-brain connection by going to the classical approximation is absurd: it amounts to trying to understand something in an approximation that eliminates the effect you are trying to study.

Quantum mechanics arose during the twentieth century. Scientists discovered, empirically, that the principles of classical physics were not correct. Moreover, they were wrong in ways that no minor tinkering could ever fix. The *basic principles* of classical

physics were thus replaced by *new basic principles* that account uniformly both for all the successes of the older classical theory and also for all the newer data that is incompatible with the classical principles.

The most profound alteration of the fundamental principles was to bring the consciousness of human beings into the basic structure of the physical theory. In fact, the whole *conception of what science is* was turned inside out. The core idea of classical physics was to describe the “world out there,” with no reference to “our thoughts in here.” But the core idea of quantum mechanics is to describe *our activities as knowledge-seeking human agents, and the knowledge that we thereby acquire*. Thus quantum theory involves, basically, what is “in here,” not just what is “out there.”

The basic philosophical shift in quantum theory is the *explicit* recognition that science is about *what we can know*. It is fine to have a beautiful and elegant mathematical theory about a *really existing physical world out there* that meets a lot of intellectually satisfying criteria. But the essential demand of science is that the theoretical constructs be tied to the experiences of the human scientists who devise ways of testing the theory, and of the human engineers and technicians who both participate in these test, and eventually put the theory to work. So the structure of a proper physical theory must involve not only the part describing the behavior of the not-directly-experienced theoretically postulated entities, expressed in some appropriate symbolic language, but also a part describing the human experiences that are pertinent to these tests and applications, expressed in the language that we actually use to describe such experiences to ourselves and each other.

Finally we need some “bridge laws” that specify the connection between the concepts described in these two different languages.

Classical physics met these requirements in a rather trivial kind of way, with the relevant experiences of the human participants being taken to be direct apprehensions of various gross behaviors of large-scale properties of big objects composed of huge numbers of the tiny atomic-scale parts. And these apprehensions were taken to be *passive*: they had no effect on the behaviors of the systems being studied. But the physicists who were examining the behaviors of systems that depend sensitively upon the behaviors of their tiny atomic-scale components found themselves forced to go to a less trivial theoretical arrangement, in which the human agents were no longer passive observers, but were *active participants* in ways that contradicted, and were impossible to comprehend within, the general framework of classical physics, *even when the only features of the physically described world that the human beings observed were large-scale properties of measuring devices*. The sensitivity of the behavior of the devices to the behavior of some tiny atomic-scale particles propagates in such a way that the acts of observation by the human observers of *large scale properties of the devices* could no longer be regarded as passive. Thus the core structure of the basic general physical theory became transformed in a profound way: the connection between physical behavior and human knowledge was changed from a one-way bridge to a mathematically specified two-way bridge. This revision must be expected to have important ramifications in neuroscience, because the issue of the connection between mind (the psychologically described aspects of a human

being) and brain/body (the physically described aspects of that person) has recently become a matter of central concern in neuroscience.

This original formulation of quantum theory was created mainly at an Institute in Copenhagen directed by Niels Bohr, and is called “The Copenhagen Interpretation.” Due to the profound strangeness of the conception of nature entailed by the new mathematics, the Copenhagen strategy was to refrain from making any ontological claims, but to take, instead, a purely pragmatic stance. Thus the theory was formulated *basically* as a set of practical rules for how scientists should go about their tasks of acquiring knowledge, and then using this knowledge in practical ways. Speculations about “what the world out there is really like” were regarded as “metaphysics,” not real science.

The most profound change in the principles is encapsulated in Niels Bohr dictum that “ in the great drama of existence we ourselves are both actors and spectators.” (Bohr, 1963: 15 & 1958: 81) The emphasis here is on “actors”: in classical physics we were mere spectators.

Copenhagen quantum theory is about the relationships between human agents (called *participants* by John Wheeler) and the systems that they act upon. In order to achieve this conceptualization the Copenhagen formulation separates the physical universe into two parts, which are described in two different languages. One part is the observing human agent and his measuring devices. That part is described in mental terms - in terms of our instructions to colleagues about how to set up the devices, and our reports of what we

then “see,” or otherwise consciously experience. The other part of nature is *the system that the agent is acting upon*. That part is described in physical terms - in terms of mathematical properties assigned to tiny space-time regions.

That approach works very well in practice. However, it seems apparent that the body and brain of the human agent, and his devices, are parts of the physical universe, and hence that a complete theory ought to be able to describe also our bodies and brains in physical terms. On the other hand, the structure of the theory depends critically also upon aspects of reality described in mentalistic language as intentional actions and experiential feedbacks.

The great mathematician and logician John von Neumann reformulated the theory in a rigorous way that places the bodies and brains of the agents, along with their measuring devices, in the physical world, *while retaining those mentalistically described properties of the agents that are essential to the structure of the theory*. It is this von Neumann formulation that provides a natural science-based account of how your mental intentions influence the activities of your brain.

Von Neumann identifies two very different processes that enter into the quantum theoretical description of the evolution of a physical system. He calls them Process I and Process II (Von Neumann, 1955: 418). Process II is the analog in quantum theory of the process in classical physics that takes the state of a system at one time to its state at a later time. This Process II, like its classical analog, is *local* and *deterministic*. However,

Process II by itself is not the whole story: it generates physical worlds that do not agree with human experiences. For example, if Process II were the *only* process in nature then the quantum state of the moon would represent a structure smeared out over large part of the sky, and each human body-brain would likewise be represented by a structure smeared out continuously over a huge region.

To tie the quantum mathematics to human experience in a rationally coherent and mathematically specified way quantum theory invokes *another process*, which Von Neumann calls Process I.

Any physical theory must, in order to be complete, specify how the elements of the theory are connected to human experience. In classical physics this connection is part of a *metaphysical* superstructure: it is not part of the core dynamical description. But in quantum theory this connection of the mathematically described physical state to human experiences is part of the essential dynamical structure. And this connecting process is not passive: it does not represent a mere *witnessing* of a physical feature of nature by a passive mind. Rather, the process is active: it injects into the physical state of the system being acted upon properties that depend upon the intention of the agent.

Quantum theory is built upon the practical concept of intentional actions by agents. Each such action is expected or intended to produce an experiential response or feedback. For example, a scientist might act to place a Geiger counter near a radioactive source, and expect to see the counter either “fire” during a certain time interval or not “fire” during

that interval. The experienced response, “Yes” or “No”, to the question “Does the counter fire during the specified interval?” specifies one bit of information. Quantum theory is thus an information-based theory built upon the knowledge-acquiring actions of agents, and the knowledge that these agents thereby acquire.

Probing actions of this kind are performed not only by scientists. Every healthy and alert infant is engaged in making willful efforts that produce experiential feedbacks, and he/she soon begins to form expectations about what sorts of feedbacks are likely to follow from some particular kind of effort. Thus both empirical science and normal human life are based on paired realities of this action-response kind, and our physical and psychological theories are both basically attempting to understand these linked realities within a rational conceptual framework.

The basic building blocks of quantum theory are, then, a set of intentional actions by agents, and for each such action an associated collection of possible “Yes” feedbacks, which are the possible responses that the agent can judge to be in conformity to the criteria associated with that intentional act. For example, the agent is assumed to be able to make the judgment “Yes” the Geiger counter clicked or “No” the Geiger counter did not click. Science would be difficult to pursue if scientists could make no such judgments about what they were experiencing.

All known physical theories involve idealizations of one kind or another. In quantum theory the main idealization is not that every object is made up of miniature planet-like

objects. It is rather that there are agents that perform intentional acts each of which can result in a feedback that may conform to a certain criterion associated with that act. One bit of information is introduced into the world in which that agent lives, according to whether the feedback conforms or does not conform to that criterion. Thus knowing whether the counter clicked or not places the agent on one or the other of two alternative possible separate branches of the course of world history.

These remarks reveal the enormous difference between classical physics and quantum physics. In classical physics the elemental ingredients are tiny invisible bits of matter that are idealized miniaturized versions of the planets that we see in the heavens, and that move in ways unaffected by our scrutiny, whereas in quantum physics the elemental ingredients are intentional actions by agents, the feedbacks arising from these actions, and the effects of our actions on the physical states that embody or carry this information.

Consideration of the character of these differences makes it plausible that quantum theory may be able to provide the foundation of a scientific theory of the human person that is better able than classical physics to integrate the physical and psychological aspects of his nature. For quantum theory describes the effects of a person's intentional actions upon the physical world, whereas classical physics systematically leaves these effects out.

An intentional action by a human agent is partly an intention, described in psychological terms, and partly a physical action, described in physical terms. The feedback also is partly psychological and partly physical. In quantum theory these diverse aspects are all

represented by logically connected elements in the mathematical structure that emerged from the seminal discovery of Heisenberg. That discovery was that in order to get the quantum generalization of a classical theory one must formulate the theory in terms of *actions*. A key difference between numbers and actions is that if A and B are two actions then AB represents the action obtained by performing the action A upon the action B. If A and B are actions then generally AB is different from BA: the order in which actions are performed matters.

The intentional actions of agents are represented mathematically in Heisenberg's space of actions. Here is how it works.

Each intentional action depends, of course, on the intention of the agent, and upon the state of the system upon which this action acts. Each of these two aspects of nature is represented within Heisenberg's space of actions by an action. The idea that a "state" should be represented by an "action" may sound odd, but Heisenberg's key idea was to replace what classical physics took to be a "being" by a "doing." I shall denote the action that represents the state being acted upon by the symbol S.

An intentional act is an action that is intended to produce a feedback of a certain conceived or imagined kind. Of course, no intentional act is sure-fire: one's intentions may not be fulfilled. Hence the intentional action puts in play a process that will lead either to a confirmatory feedback "Yes," the intention is realized, or to the result "No", the "Yes" response did not occur.

The effect of this intentional mental act is represented mathematically by an equation that is one of the key equations of quantum theory. This equation represents, within the quantum mathematics, the effect of the Process I mental action upon the quantum state S of the system being acted upon. The equation is:

$$S \rightarrow S' = PSP + (I-P)S(I-P).$$

This formula exhibits the important fact that this Process I action changes the state S of the system being acted upon into a new state S', which is a *sum* of two parts.

The first part, PSP, represents the possibility in which the experiential feedback called “Yes” appears, and the second part, (I-P)S(I-P), represents the alternative possibility “No”, this feedback does not appear. Thus the intention of the action and the associated experiential feedback are tied into the mathematics that describes the dynamics of the physical system being acted upon.

The symbol P is important. It represents the fact that the Process I depends on *the intention of the agent*. The action represented by the symbol P, acting both on the right and on the left of S, is the action of eliminating from the state S all parts of S except the “Yes” part. That particular retained part is determined by the intentional choice of the agent. The symbol I is the unit operator, which is essentially multiplication by 1, and the

action of (I-P), acting both on the right and on the left of S, is, analogously, to eliminate from S all parts of S except the “No” parts.

Notice that Process I produces the *sum* of the two alternative possible feedbacks, not just one or the other. Since the feedback must either be “Yes” or “No = Not-Yes,” one might think that Process I, which *keeps* both the “Yes” and the “No” parts, would do nothing. But that is not correct! This is a key point. It can be made quite clear by noticing that S can be written as a sum of four parts, only two of which survive the Process I action:

$$S = PSP + (I-P)S(I-P) + PS(I-P) + (I-P)SP.$$

This formula is a strict identity. The dedicated reader can quickly verify it by collecting the contributions of the four occurring terms PSP, PS, SP, and S, and verifying that all terms but S cancel out. This identity shows that the state S is a sum of four parts, *two of which are eliminated by Process I*.

But this means that Process I has a *nontrivial effect* upon the state being acted upon: it eliminates the two terms that correspond neither to the appearance of a “Yes” feedback nor to the failure of the “Yes” feedback to appear.

That is the *first key point*: quantum theory has a specific dynamical process, Process I, which specifies the effect upon a physical system of an *intention-controlled act* of a human agent.

Free Choices

The second key point is this: the agent's choices are "free choices," *in the specific sense specified below.*

Orthodox quantum theory is formulated in a realistic and practical way. It is structured around the activities of human agents, who are considered able to 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." (Bohr, 1958: 73}

This freedom of action stems from the fact that in the original Copenhagen formulation of quantum theory the human experimenter is considered to stand 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.”

Probabilities

The predictions of quantum theory are generally statistical: only the *probabilities* that the agent will experience each of the alternative possible feedbacks are specified. Which of these alternative possible feedbacks will actually occur in response to a Process I action is not determined by quantum theory.

The formula for the probability that the agent will experience the feedback ‘Yes’ is $\text{Tr PSP}/\text{Tr S}$, where the symbol Tr represents the trace operation. This trace operation means that the actions act in a cyclic fashion, so that the rightmost action acts back around upon the leftmost action. Thus, for example, $\text{Tr ABC}=\text{Tr CAB}=\text{Tr BCA}$. The product ABC represents the result of letting A act upon B , and then letting that product AB act upon C . But what does C act upon? Taking the trace of ABC means specifying that C acts back around on A .

An important property of a trace is that the trace of any of the sequences of actions that we consider must always give a positive number or zero. Thus this trace operation is what ties the actions, as represented in the mathematics, to measurable numbers.

Von Neumann generates his form of quantum theory by recognizing that Process I describes an influence of a mentalistically described aspect of reality upon a physically described aspect, and by expanding the physically described part to include the brain that is connected to the mentalistically described stream of consciousness. Thus Process I represents, in the end, a dynamical influence of the mind of an agent upon his brain

But if the agent is *free* to choose which action to take, and if the *intention* of that action, represented by P, affects the state being acted upon, then the agent's free mental choice of intention influences the state S being acted upon, which in Von Neumann quantum theory is his/her brain.

This is the important conclusion: Orthodox (von Neumann) quantum theory has a Process I action that, on the one hand, is need to tie the theory to human experience, and that, on the other hand, produces a dynamical effect upon the state of his brain.

It is worthwhile to reflect for a moment on the ontological aspects of Von Neumann quantum theory. Von Neumann himself, being a clear thinking mathematician, said very little about ontology. But he called the mentalistically described aspect of the agent "his abstract 'ego'." (von Neumann, 1955: 421). This phrasing tends to conjure up the idea of a disembodied entity, standing somehow apart from the body/brain. But another possibility is that consciousness is an *emergent property* of the body-brain. Notice that some of the problems that occur in trying to defend this idea of emergence within the framework of classical physical theory disappear when one accepts the validity of

quantum theory. For one thing, one no longer has to defend against the charge that the emergent property, consciousness, has no “genuine” causal efficacy because anything it does is done already by the physically described process, independently of whether the psychologically described aspect emerges or not. If quantum theory is accepted then the causal efficacy of our thoughts is no illusion: it’s the real thing!

Another difficulty with “emergence” in a classical physics context is in understanding how the motion of a set of miniature planet-like objects, careening through space, can *be a painful experience*. But the essential nature of the “stuff” represented by a quantum event is experiential, and the mathematically described state that stores the fact that this experience has occurred is not material, it is informational. Hence there is no longer any clash with intuition: the concept of the physical stuff has changed in a way that eliminates the problem.

In this connection, Heisenberg remarked:

“The conception of the objective reality of the elementary particles has thus evaporated not into the cloud of some obscure new reality concept, but into the transparent clarity of a mathematics that represents no longer the behavior of the particle but rather our knowledge of this behavior.” (Heisenberg, 1958)

By closing in this way the conceptual gap between mental and physical properties the acceptance of quantum theory opens the way to a less problematic version of the emergent-identity theory of mind.

This pragmatic re-conceptualization of the nature of science, and of the nature of the physical universe and its connection to human thoughts, should, it would seem, be equally important in neuroscience. This is because the basic problem in neuroscience is essentially this very same problem as the one of atomic physics, namely the problem of linking, in a practically useful way, the spacetime-imbedded mathematical description of a physical system being acted upon to the psychologically described aspects of the human agents. The problem in both cases, and in science in general, is to link, in practically useful ways, the psychological language that we human beings use to communicate our normal experiences from one to another to the mathematical language of physics and physiology. Matter-based classical physics does not provide a practically useful linkage between these two languages, but agent-based, action-based quantum physics does.

According to quantum theory, consciousness is, in effect, a *causally efficacious reality* that is connected to physical brain processes in a non-local, non-reducible, non-redundant, non-illusory, and non-trivial way.

Process I is non-local because each operator P must (due to its boundedness) act not at a point, but rather over some extended region (such as a macroscopic part of a brain.) It is non-reducible because it is a real dynamical process that is neither part of, nor entailed

by, the local-deterministic mechanical Process II. It is non-redundant, non-illusory, and non-trivial for the same reason. By dealing directly with *a dynamically formulated* linkage – Process I – between the psychological language that describes the actions and knowledge of the agents and the mathematical representation of the state of the system being acted upon, quantum theory provides a pragmatic foundation for a solution to the mind-brain problem of neuroscience that is both analogous to, and an extension of, the pragmatic solution devised by physicists for the problem of creating a scientific theory of atomic phenomena.

The quantum state of a human brain is, of course, a very complex thing. But its main features can be understood by considering first a classical conception of the brain, and then folding in some key features that arise already in the case of the quantum state of a single particle, or object, or degree of freedom.

States of a Simple Harmonic Oscillator

One of the most important examples of a quantum state is the one corresponding to a pendulum, or more precisely, to what is called a “simple harmonic oscillator.” Such a system is one in which there is a restoring force that tends to push the center of the object to a single “base point” of lowest energy, and in which the strength of this restoring force is directly proportional to the distance of the center point of the object from this base point.

According to classical physics any such system has a state of lowest energy. In this state the center point of the object lies motionless at the base point. In quantum theory this system again has a state of lowest energy, but the center point is not localized at the base point: it is represented by a *cloudlike* spatial structure that is spread out over a region that extends to infinity. However, the amplitude of this cloudlike form has the shape of a bell: it is largest at the base point, and falls off in a prescribed manner as the distance the center point from the base point increases.

If one were to squeeze this state of lowest energy into a more narrow space, and then let it loose, the cloudlike form would first explode outward, but then settle into an oscillating motion. Thus the cloudlike spatial structure behaves rather like a swarm of bees, such that the more they are squeezed in space the faster they move, and the faster the squeezed cloud will explode outward when the squeezing constraint is released. These visualizable properties extend in a natural way to many-particle cases.

The Double-Slit Experiment

An important difference between the behavior of the quantum cloudlike form and the somewhat analogous *classical probability distribution* is exhibited by the famous *double-slit experiment*. If one shoots an electron, an ion, or any other quantum counterpart of a tiny classical object, at a narrow slit then if the object passes through the slit the associated cloudlike form will fan out over a wide angle. But if one opens two closely neighboring narrow slits, then what passes through the slits is described by a probability distribution that is not just the sum of the two separate fanlike structures that would be

present if each slit were opened separately. Instead, at some points the probability value will be *twice the sum* of the values associated with the two individual slits, and in other places the probability value drops nearly to zero, even though both individual fanlike structures give a large probability value at that place. These *interference* features of the quantum cloudlike structure make that structure logically different from a classical-physics probability distribution, for in the classical case the probabilities arising from the two slits would simply add, due to the fact that, according to classical principles, the particle must pass through one slit or the other, and the fact that some other slit is also open should not matter very much.

Quantum theory deals consistently with this interference effect, and all the other, non-classical properties of these cloudlike structures.

Nerve Terminals, Ion Channels, and the Need to Use Quantum Theory

Some neuroscientists who study the relationship of consciousness to brain process believe that classical physics will be adequate for that task. That belief would have been reasonable during the nineteenth century, but now, in the twenty-first, it is rationally untenable: quantum theory must in principle be used because the behavior of the brain depends sensitively upon ionic and atomic processes, and these processes involve quantum effects.

To study quantum effects in brains within an orthodox (i.e., Copenhagen or Von Neumann) quantum theory one must use the von Neumann formulation. The reason is

that *Copenhagen* quantum theory is formulated in a way that leaves out the quantum dynamics of the human observer's body and brain. But Von Neumann quantum theory takes the physical system S upon which the crucial Process I acts to be the brain of the agent. Thus Process I then describes an interaction between a person's stream of consciousness, described in mentalistic terms, and the activity in his brain, described in physical terms. That interaction drops completely out when one passes to the classical approximation. Hence ignoring quantum effects in the study of the mind-brain connection means, according to the basic principles of physics, ignoring the dynamical connection one is trying to study. One must *in principle* use quantum theory. But there is then the quantitative issue of how important the quantum effects are.

To explore that question we now consider the quantum dynamics of nerve terminals.

Nerve Terminals

Nerve terminal are essential connecting links between nerve cells. The way they work is quite well understood. When an action potential traveling along a nerve fiber reaches a nerve terminal a host of ion channels open. Calcium ions enter through these channels into the interior of the terminal. These ions migrate from the channel exits to release site on vesicles containing neurotransmitter molecules. The triggering effect of the calcium ions causes these contents to be dumped into the synaptic cleft that separates this terminal from a neighboring neuron, and these neurotransmitter molecules influence the tendencies of that neighboring neuron to "fire."

The channels through which the calcium ions enter the nerve terminal are called “ion channels.” At their narrowest points they are less than a nanometer in diameter.(Cataldi, 2002). This extreme smallness of the opening in the ion channels has profound quantum mechanical importance. The consequence is essentially the same as the consequence of the squeezing of the state of the simple harmonic operator, or of the narrowness of the slits in the double-slit experiments. The narrowness of the channel restricts the lateral spatial dimension. Consequently, the lateral velocity is forced by the *quantum uncertainty principle* to become large. This causes the cloud associated with the calcium ion to *fan out* over an increasing area as it moves away from the tiny channel to the target region where the ion will be absorbed as a whole, or not absorbed, on some small triggering site.

This spreading of the ion wave packet means that the ion may or may not be absorbed on the small triggering site. Accordingly, the vesicle may or may not release its contents. Consequently, the quantum state of the vesicle has a part in which the neurotransmitter is released and a part in which the neurotransmitter is not released. This quantum splitting occurs at every one of the trillions of nerve terminals.

What is the effect of this *necessary* incursion of the cloud-like quantum character of the ions into the evolving state of the brain?

A principal function of the brain is to receive clues from the environment, to form an appropriate plan of action, and to direct and monitor the activities of the brain and body specified by the selected plan of action. The exact details of the plan will, for a classical

model, obviously depend upon the exact values of many noisy and uncontrolled variables. In cases close to a bifurcation point the dynamical effects of noise might even tip the balance between two very different responses to the given clues, e.g., tip the balance between the ‘fight’ or ‘flight’ response to some shadowy form.

The effect of the independent superpositions of the “release” or “don’t release” options, coupled with the uncertainty in the timing of the vesicle release at each of the trillions of nerve terminals will be to cause the quantum mechanical state of the brain to become a smeared out superposition of different macro-states representing different alternative possible plans of action. As long as the brain dynamics is controlled wholly by Process II - which is the quantum generalization of the Newtonian laws of motion of classical physics - all of the various alternative possible plans of action will exist in parallel, with no one plan of action singled out as the one that will actually occur. Some other process, beyond the local deterministic Process II, is required to pick out one particular real course of physical events from the smeared out mass of possibilities generated by all of the alternative possible combinations of vesicle releases at all of the trillions of nerve terminals. That other process is Process I, which brings in the action of the mind of the agent upon his brain.

This explanation of why quantum theory is pertinent to brain dynamics has focused on individual calcium ions in nerve terminals. That argument pertains to the *Process II component* of brain dynamics.

The equally important *Process I component* of the brain dynamics, which brings the mind of the agent into the dynamics, must be analyzed in terms of a completely different set of variable, namely certain *quasi-stable macroscopic degrees of freedom*. These specify the brain structures that enjoy the stability or persistence, and the causal connections, needed to represent intentional actions and expected feedbacks.

The states of the brain that will be singled out by the actions P that specify the form of a Process I action will be more like the lowest-energy state of the simple harmonic oscillator discussed above, which tends to endure for a long time, or like the states obtained from such lowest-energy states by spatial displacements and shifts in velocity. Such states tend to endure as oscillating states, rather than immediately exploding. In other words, in order to get the needed stability properties the projection operators P corresponding to intentional actions should be constructed out of *oscillating states of macroscopic subsystems of the brain*, rather than out of sharply defined spatial states of the individual particles. The pertinent states will be functionally important brain analogs of a collection of oscillating modes of a drumhead, in which large collections of particles of the brain are moving in a coordinated way that will lead on to further coordinated activity.

In summary, the *need to use quantum theory* in brain dynamics arises from the dispersive quality of *Process II* action at the level of the ionic, and electronic, and atomic components of the brain. Hence *that* analysis is carried out at the individual-particle level. However, the opposing integrative and selective action, Process I, which brings in

the mental (i.e., psychologically described) aspect involves a completely different set of variables. Process I is specified by an operator P that singles out a quasi-stable large-scale pattern of brain activity that is the brain correlate of a particular mental intention.

It should be mentioned here that the actions P are *non-local*: they must act over extended regions, which can, and are expected to, cover large regions of the brain. Each conscious act is associated with a Process I action that coordinates and integrates activities in diverse parts of the brain. A conscious thought, as represented by the Von Neumann Process I, effectively grasps as a whole an entire quasi-stable macroscopic brain activity.

Choices of the Process I Actions

It has been emphasized that the choices of which Process I actions actually occur are “free choices,” in the sense that they are not specified by the currently known orthodox laws of physics. On the other hand, a person’s intentions surely depend upon his brain. This means that we need to understand the process that determines the choice of P, which, within the framework of contemporary physical theory, is a free choice. In other words, the laws of contemporary quantum theory, although highly restrictive, are not the whole story: there is still work to be done. Hypotheses must be formulated and tested.

According to the theory, each experience is associated with the occurrence of a Process I event. As a simple first guess, let us assume, following a suggestion of Benjamin Libet and other psychologists, that the occurrence of a Process I action is triggered by a “consent” on the part of the agent, and that the rapidity with which consent is given can be increased by “mental effort.”

To get a definite model, let $\{P\}$ be the set of actions P that correspond to possible mental intentions. Then let $P(t)$ be the “most probable P in $\{P\}$ ”, where the probability is defined by brain state $S(t)$. In equations this most probable P in $\{P\}$ would be the P in $\{P\}$ that maximizes $\text{Tr } PS(t)P/\text{Tr } S(t)$. The first hypothesis will be that the Process I event specified by $P(t)$ will occur if and only if a “consent” is given at time t .

To make mind efficacious it is assumed that “consent” depends on the *mental realities* associated with $P(t)$, and that “consent” can be given with a rapidity that is increased if the mental evaluation includes a feeling of effort. This simplest model makes the choice of the Process I action dependent both upon the physical state of the agent’s brain, and also upon the mental realities associated with that action.

It is assumed, here, that the consent associated with “hearing a nearby clap of thunder” is essentially passive: it will occur unless attention is strongly focused elsewhere. The important input of the mental aspect arises from the *effortful* focusing of mental attention on some intention.

Quantum theory *explains* how such a mental effort can strongly influence the course of brain events. Within the Von Neumann framework this potentially very strong effect of mind upon brain is an automatic consequence of a well-known and well studied feature of quantum theory called The Quantum Zeno Effect.

The Quantum Zeno Effect

If one considers only passive consents, then it is very difficult to identify any clean empirical effect of this intervention, apart from the production of low-level awareness. In the first place, the empirical averaging over the “Yes” and “No” possibilities tends to wash out all measurable effects. Moreover, the passivity of the mental process means that we have no independent self-controlled mental variable.

But the study of effortful and intentionally controlled attention brings in two empirically accessible variables, the intention and the amount of effort. It also brings in the important physical Quantum Zeno Effect. This effect is named for the Greek philosopher Zeno of Elea, and was brought into prominence in 1977 by the physicists Sudarshan and Misra (1977). It gives a name to the fact that repeated and closely-spaced intentional acts can effectively hold the “Yes” feedback in place for an extended time interval that depends upon the *rapidity at which the Process I actions are happening*. According to our quantum model, this rapidity is controlled by the amount of effort being applied.

This Quantum Zeno Effect is, from a theoretical point of view, a very clean consequence of the Von Neumann theory. It was first identified *theoretically*, and the theoretical predictions were later confirmed in many experimental contexts. The first confirmations were in the realm of atomic and molecular physics.

Consider an atom that has absorbed a photon of energy. That energy has kicked one of the atom's electrons into what's called a higher orbital, kind of like a super-massive asteroid kicking Mercury into Venus's orbit, and the atom is said to be "excited." But the electron wants to go back where it came from, to its original orbital, which it can do if the atom releases a photon. When the atom does so is one of those chance phenomena, like when a radioactive atom will decay: the atom has some chance of releasing a photon (and allowing the electron to return home) within a given period of time. Physicists can measure whether the atom is still in its initial state or not. If they carry out such measurements repeatedly and rapidly, physicists have found, we can keep the atom in its initial state. This is the Quantum Zeno Effect: such a rapid series of observations locks a system into that initial state. The more frequent the observations of a quantum system, the greater the suppression of transitions out of the initial quantum state. Taken to the extreme, observing continuously whether an atom is in a certain quantum state keeps it in that state forever. For this reason, the Quantum Zeno Effect is also known as the watched pot effect. The mere act of rapidly asking questions of a quantum system freezes it in a particular state, preventing it from evolving as it would if we weren't peeking. Simply observing a quantum system suppresses certain of its transitions to other states.

How does it work? Consider this experiment. An ammonia molecule consists of a single atom of nitrogen and three atoms of hydrogen. The arrangement of the four atoms shifts over time because all the atoms are in motion. Let's say that at first the nitrogen atom sits atop the three hydrogens, like an egg nestled on a tripod (The nitrogen atom has only two options, to be above or below the trio. It cannot be in between.). The wave function that

describes the position of the nitrogen is almost all concentrated in this configuration; that is, the probability of finding the nitrogen at the apex is nearly 100 percent. Left to its own devices, the wave function would shift as time went by, reflecting the increasing probability that the nitrogen atom would be found below the hydrogens. But before the wave function shifts, we make an observation. The act of observation causes the wave function (which, again, describes the probability of the atom being in this place or that one) to collapse from several probabilities into a single actuality. This is all standard quantum theory, the well-established collapse of the wave function following an observation.

But something interesting has happened. "The wave function has ceased oozing toward the bottom," as Sudarshan and his colleague Rothman explained (Rothman; 1998) "it has been 'reset' to the zero position. And so, by repeated observations at short intervals, . . . one can prevent the nitrogen atom from ever leaving the top position." If you rapidly and repeatedly ask a system, *are you in this state or are you not?*, by making observations designed to ascertain whether or not the nitrogen atom is where it began, the system will not evolve in the normal way. It will become, in a sense, frozen. An answer of "Yes" to the posed question [in this case: Is the nitrogen atom on top?] will become fixed and unchanging. The state will be forced to stay longer within the realm that provides a "Yes" answer.

Quantum Zeno has been verified experimentally many times. One of the neatest confirmations came in a 1990 study at the National Institute of Standards and

Technology. There, researchers measured the probability that beryllium ions would decay from a high-energy to a low-energy state. As the number of measurements per unit time increased, the probability of that energy transition fell off; the beryllium atoms stayed in their initial, high-energy state because scientists kept asking them, “So, have you decayed yet?” The watched pot never boiled. As Sudarshan and Rothman concluded, "One really can stop an atomic transition by repeatedly looking at it."

This effect is a very special case of the general fact that if a sequence of similar Process I events occur rapidly [on the time scale of the macroscopic oscillations associated with the associated actions P] then the “Yes” outcome can be held in place in the face of strong Process II mechanical forces that would tend to quickly produce the “No” feedback. This means that agents whose efforts can influence the rapidity of Process I actions would enjoy a survival advantage over competitors that lack this feature, for they could sustain beneficial activities longer than their Process I deprived competitors. This gives the leverage needed to link mind to natural selection, and also the leverage needed to allow us to link our minds to our physical actions. For these efforts will then have intention-controlled physical effects, and this linkage can be discovered, and integrated into behavior, by trial and error processes.

Support from Psychology

The empirical evidence cited above for the actual existence of the theoretically mandated Quantum Zeno Effect comes from physics experiments. But, according to the theory, the effect should manifest itself also in the realm of psychology.

A person's experiential life is a stream of conscious experiences. The person's experienced "*self*" is *part* of this stream of consciousness: it is not an extra thing that is outside or apart from the stream. In James's words "*thought is itself the thinker*, and psychology need not look beyond." The "self" is a slowly changing "fringe" part of the stream of consciousness. It provides a background cause for the central focus of attention.

The physical brain, evolving mechanically in accordance with the local deterministic Process II does most of the necessary work, without the intervention of Process I. It does its job of creating, on the basis of its interpretation of the clues provided by the senses, a suitable response. But, due to its quantum nature, the brain necessarily generates an amorphous mass of overlapping and conflicting templates for action. Process I acts to extract from this jumbled mass of possibilities a dynamically stable configuration in which all of the quasi-independent modular components of the brain act together in a maximal mutually supportive configuration of non-discordant harmony that tends to prolongs itself into the future and produce a characteristic subsequent feedback. This is the preferred "Yes" state PSP that specifies the form of the Process I event. But the quantum rules do not assert that this preferred part of the prior state S necessarily comes into being: they assert, instead, that if this process is activated---say by some sort of "consent"---then this "Yes" component PSP will come into being with probability

$\text{Tr PSP} / \text{Tr S}$.

And the rate at which consents are given is assumed to be increasable by mental effort.

The phenomena of “will” is understood in terms of this effortful control of Process I, which can, by means of the Quantum Zeno Effect, override strong mechanical forces arising from Process II, and cause a large deviation of brain activity from what it would be if no mental effort were made.

Does this quantum-physics-based conception of the connection between mind and brain explain anything in the realm of psychology?

Consider some passages from “Psychology: The Briefer Course”, written by William James. In the final section of the chapter on attention James(1892: 227) writes:

“I have spoken as if our attention were wholly determined by neural conditions. I believe that the array of things we can attend to is so determined. No object can catch our attention except by the neural machinery. But the amount of the attention which an object receives after it has caught our attention is another question. It often takes effort to keep mind upon it. We feel that we can make more or less of the effort as we choose. If this feeling be not deceptive, if our effort be a spiritual force, and an indeterminate one, then of course it contributes coequally with the cerebral conditions to the result. Though it introduce no new idea, it will deepen and prolong the stay in consciousness of innumerable ideas which else would fade more quickly away.”

In the chapter on will, in the section entitled "Volitional effort is effort of attention" James (1892: 417) writes:

"Thus we find that we reach the heart of our inquiry into volition when we ask by what process is it that the thought of any given action comes to prevail stably in the mind."

and later

"The essential achievement of the will, in short, when it is most 'voluntary,' is to attend to a difficult object and hold it fast before the mind. ... Effort of attention is thus the essential phenomenon of will."

Still later, James says:

"Consent to the idea's undivided presence, this is effort's sole achievement."... "Everywhere, then, the function of effort is the same: to keep affirming and adopting the thought which, if left to itself, would slip away."

This description of the effect of mind on the course of mind-brain process is remarkably in line with *what had been proposed independently from purely theoretical considerations of the quantum physics of this process*. The connections specified by James are *explained* on the basis of the same dynamical principles that had been

introduced by physicists to explain atomic phenomena. Thus the whole range of science, from atomic physics to mind-brain dynamics, is brought together in a single rationally coherent theory of an evolving cosmos that consists of a physical reality that is constituted not of matter but of an action-based reality that determines propensities or tendencies for Process I events to occur.

In the quantum theory of mind-brain being described here there are two separate processes. First, there is the unconscious mechanical brain process called Process II. As discussed at length in the book, *Mind, Matter, and Quantum Mechanics* (Stapp, 1993: 150), this brain processing involves dynamical units that are represented by complex patterns of neural activity (or, more generally, of brain activity) that are "facilitated" (i.e., strengthened) by use, and are such that each unit tends to be activated as a whole by the activation of several of its parts. The activation of various of these complex patterns by cross referencing---i.e., by activation of several of its parts---coupled to feed-back loops that strengthen or weaken the activities of appropriate processing centers, appears to account for the essential features of the mechanical part of the dynamics in a way that in many cases is not greatly different from that of a classical model, except for the creation of a superposition of a host of parallel possibilities that according to the classical concepts could not exist simultaneously.

The second process, Von Neumann's Process I, is needed in order to select what actually happens from the continuum of alternative possibilities generated by Process II.

Process I, which is connected to conscious awareness and to what actually happens, has itself two modes. The first involves mere passive consent, and temporally isolated events; the second involves mental effort, and a sequence of temporally closely spaced events that bring importantly into play the Quantum Zeno Effect. The first mode involves passive processing, and exploits the massively parallel processing capacities of process II, whereas the second mode involves an effortfully sustained sequence of Process I events.

Active Process I intervention has, according to the quantum-physics-based theory described here, a distinctive form. It consists of a sequence of intentional actions the rapidity of which can be increased with effort. Effort-induced speed-up of the rate of occurrence of these events can, by means of the quantum Zeno effect, keep attention focused on an intention.

Effort can, by increasing the number of intentional events per second, increase the input of mental processing into brain activity.

An extended discussion of non-trivial agreement of these features with a large body of data from the field of the psychology of attention is described in Stapp (2001)

Mental Action in Neuroscience

Scientists in different fields are to some extent free to choose what sort of models or theories they use to organize, explain, understand, and predict the observed features of

the data in their field, and to guide their further inquiries. On the other hand, the ideal of *the unity of science* gives precedence to models that mesh with the basic principles of physics, or at least do not contradict them.

On the basis of this ideal it would seem that, for experiments that deal directly with the effects of self-directed mental intentions upon brain activity, the preferred theoretical framework would be one based upon contemporary physical theory, rather than one based upon an approximation that, according to contemporary physical theory, systematically eliminates from the more exact theory some important effects of mental intention upon the brain that seem to be exactly of the kind needed to account for the neuroscience data.

The conceptual structure of the more accurate quantum model seems eminently better suited to the analysis of this data than models based on the classical approximation. The quantum treatment not only *retains* a mechanism that coherently accounts for the data, it is also much simpler. For, just as in the treatment of atomic systems, it brings directly into the *dynamical* description of the phenomena a representation of the *phenomenological* description of those phenomena. It ties the mentalistic language that we human beings use to communicate to each other the facts about the phenomena into the physical description of the phenomena.

The foregoing account of the quantum approach is general, but somewhat abstract. To make it more tangible and concrete let us consider the experiments of Ochsner et al.

(2002) - described also in Chapter Seven of this volume - with particular attention to the following four key questions:

1. How does the quantum mechanism work in this case, in comparison to what the classical account would say?
2. How do we account for the rapid changes occurring in large neural circuits involving millions of neurons during conscious and voluntary regulation of brain activity?
3. How does consciousness “know” where and how to interact in the brain in order to produce a specific psychological effect?
4. Is consciousness localized, and, if so, how and in what sense; or does it lie, instead, “outside of space”?

Reduced to its essence the experiment consists first of a training phase in which the subject is taught how to distinguish, and respond differently to, two instructions given while viewing emotionally disturbing visual images: ATTEND (meaning passively “be aware of, but not try to alter, any feelings elicited by”) or REAPPRAISE (meaning actively “reinterpret the content so that it no longer elicits a negative response”). The subjects then perform these mental actions during brain data acquisition. The visual stimuli, when passively attended to, activate limbic brain areas and when actively reappraised activate prefrontal cerebral regions.

From the classical materialist point of view this is essentially a conditioning experiment, where, however, the “conditioning” is achieved via linguistic access to cognitive faculties. But how do the cognitive realities involving “knowing,” “understanding,” and “feeling” arise out of motions of the miniature planet-like objects of classical physics, which have no trace of any experiential quality? And how do the vibrations in the air that carry the instructions get converted into feelings of understanding? And how do these feelings of understanding get converted to effortful actions, the presence or absence of which determine whether the limbic or frontal regions of the brain will be activated.

Within the framework of classical physics these connections between feelings and brain activities are huge mysteries. The classical materialist claim is that *someday* these connections will be understood. But the basic question is whether these connections will ever be understood in terms of a physical theory that is known to be false, and that, moreover, is false in ways that, according to contemporary physical theory, systematically exclude the causes of the correlations between the psychological and physiological aspects of the mind-brain system that these neuropsychology experiments reveal. Or, on the other hand, will the eventual understanding of this linkage accord with causal linkage between mental realities and brain activities that orthodox (Von Neumann) contemporary physical theory entails.

There are important similarities and also important differences between the classical and quantum explanations of the experiments of Ochsner et al. In both approaches the particles in the brain can be conceived to be collected into nerves and other biological

structures, and into fluxes of ions and electrons, which can all be described reasonably well in essentially classical terms. However, in the classical description the dynamics is well described in terms of the local deterministic classical laws that govern these classical quantities, insofar as they are precisely defined.

Quantum theory asserts, however, that the condition that these classical quantities be *precisely defined* is unrealistic: Heisenberg's uncertainty principle asserts that this assumption is not justified: one must accept at least some small amount of cloudlike uncertainty. But small uncertainties rapidly grow into larger uncertainties. The discussion of the ionic motions in nerve terminals exemplifies this growth of uncertainty: the state of the brain rapidly fans out into a state that encompasses many possible experiential states.

This incursion into the dynamics of growing uncertainties renders the classical approach basically incomplete: it can never lead to well defined experiential states, except by actually violating the quantum laws.

[There is a well-known and powerful process in quantum theory that strongly influences this expansion of the state of the brain into a state that encompasses many alternative experiential possibilities. It is called "environmental decoherence." The interactions of the brain with its environment makes the state S of the brain into what is called a "mixture." This means that the interference effects between significantly different classically describable possibilities becomes markedly attenuated. That effect is, however, already completely accounted for in the Von Neumann state S of the brain:

environmental decoherence in no way upsets or modifies the Von Neumann theory described here. Indeed it makes that theory basically accessible to neuroscientists by converting the complex mathematical concept of a quantum state into a structure that can be visualized as simply a collection of virtual classically conceived states: the quantum state of the brain is effectively transformed by environmental decoherence effects into an ensemble of classically describable potentialities that become converted to experiential realities by a Process I action. Thus the quantum brain dynamics becomes much easier both to conceive and to describe because of environmental decoherence effect allows classical language and imagery to be validly used in an important way. But it has never been shown to obviate the need for Process I.]

One could, despite violating the quantum laws, try to pursue a quasi-classical calculation. This would be a classical-type computation with the quantum-mandated uncertainties folded in as probability distributions, and with certain classically describable brain states identified as the “neural correlates” of the various possible experiential states. One could then produce, in principle, the same general kinds of statistical predictions that quantum theory would give.

This sort of quasi-classical approach would, in fact, probably give results very similar to quantum theory for situations arising from “passive attention.” For in these cases mind is acting essentially as a passive witness, in a way that is basically in line with the ideas of classical physics.

But quantum theory was designed to deal with the other case, in which the conscious action of an agent – to perform some particular probing action - enters into the dynamics in an essential way. Within the context of the experiment by Ochsner et al., quantum theory provides, via the Process I mechanism, an explicit means whereby the successful effort to “rethink feelings” actually causes - by catching and actively holding in place - the prefrontal activations critical to the experimentally observed deactivation of the amygdala and orbitofrontal cortex. The resulting *intention-induced modulation* of limbic mechanisms that putatively generate the frightening aversive feelings associated with passively attending to the target stimuli is the key factor necessary for the achievement of the emotional self-regulation seen in the active cognitive reappraisal condition. Thus, within the quantum framework, the causal relationship between the mental work of mindfully reappraising and the observed brain changes presumed to be necessary for emotional self-regulation is *dynamically* accounted for. Furthermore, and crucially, it is accounted for in ways that fully allow for communicating to others the means utilized by living human experimental subjects to attain the desired outcome. The classical materialist approach to these data, as detailed earlier in this chapter, by no means allows for such effective communication. Analogous quantum mechanical reasoning can of course be utilized *mutatis mutandis* to explain the data of Beauregard (2001) and related studies of self-directed neuroplasticity (see Schwartz & Begley, 2002).

Quantum theory resolves, within a scientific context, the problem of the connection between the psychologically and physically described features of the mind-brain system by, first, taking the linguistic/semantic modes of expression that scientists use to

communicate experimental conditions and facts to one another, and to others, to be descriptions of psychological realities that, in essence, are what they seem to be, and do what they seem to do, and, second, specifying the dynamical equation that determines how these psychologically described realities act upon physical brain states.

The second question is: How do we account for the rapid changes induced by mental effort in large brain circuits?

The answer is that the non-local operator P that represents the intention singles out a large quasi-stable and functionally important brain state that is likely to produce the expected feedbacks. Large intention-controlled functionally effective brain activities are singled out and linked to mental effort through *learning*, which depends upon the fact that the mental efforts, per se, have physical consequences. A “Yes” outcome actualizes such a functional state. Thus quantum theory provides the mathematical machinery for linking mentalistically described functional properties to the physically described macroscopic properties of the brain that implements them. No comparable linkage is provided by classical physics, which would appear to be constitutionally ill-equipped to accommodate causally efficacious mental actions.

The third question is: How does consciousness “know” where and how to interact in the brain in order to produce a specific psychological effect?

The answer is that felt intentions, per se, have physical consequences, and thence experiential consequences. Hence an agent can learn, by trial and error, how to select an intentional action that is likely to produce a feedback that fulfills an intention.

The fourth question is: Is consciousness localized, and, if so, how and in what sense; or does it lie, instead, “outside of space”?

Each conscious event is associated with a Process I action that involves an action P that is necessarily non-local, for mathematical reasons. Moreover, the “Yes” part must have the functional properties needed to set in motion the brain-body activity that is likely to produce the intended feed-back experience. Thus each conscious action would, in order to meet these requirements, act over some functionally characterized extended portion of the brain. [In fact, for reasons that go well beyond the scope of this chapter, this event also induces effects in faraway places: these effects are the causes, within the Von Neumann ontology, of the long-range non-local effects associated with the famous theorem of John Bell (1964).]

Conclusions and summary

The key point of this entire chapter is simply this: neuropsychology is greatly simplified by accepting the fact that brains must in principle be treated quantum mechanically. Accepting that obvious fact means that the huge deferred-to-the-future question of how mind is connected to a classically described brain must, in principle, be replaced by the already resolved question of how mind is connected to a quantum mechanically described

brain. That shift resolves the problem of accounting for the dynamic linkage between linguistic/semantic modes communication used in setting up experiments involving cognitive control of emotions and the physical description of the brains of subjects, by adopting the same pragmatic solution that atomic physicists adopted when faced with this *same* problem of accounting coherently for the effects of *mentalistically described human intentional actions upon the physically described systems that those actions act upon*. This solution is encapsulated in Process I. The benefits of adopting the pragmatic quantum approach may be as important to progress in neuroscience as they were in atomic physics.

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