W. L. Miranker

A Quantum State Model of Consciousness

Abstract: *We introduce a quantum state representation of the information being processed in neuronal structures. The movement of information from one such structure to a second is characterized as a (quantum) measurement of the first structure by the second. The value of such a measurement is an observable (external) property of matter. The associated collapsed quantum state, a dual encoding of that measurement, is a non-observable (internal) property of matter. The quantum measurement collapse process itself is shown to be a form of experience of the measurement process in terms of which a model and explanation of consciousness is formulated. Using model neurons we show how neuronal information processing effects may be given a quantum characterization. The techniques developed are employed to frame a model of qualia.*

I: Introduction

We develop a quantum state model of consciousness, the phenomenon of experience that we all know. That is, we address what has been termed the hard problem of consciousness by Chalmers (1995; 1996). The aim here is to bring the methods of third-person, objective science to the study of consciousness, itself an apparently first-person phenomenon. We begin with the development of a quantum-like model of information processing in the brain. Then we show that consciousness may be identified with a well-known aspect (namely the collapse process of a quantum measurement) of such a model.[1] The constructs of the model itself along with an application (a model of qualia) provide first results of this approach.

Correspondence: W. L. Miranker, Computer Science Department, Yale University
PO Box 208285, New Haven, CT 06520, USA.
Email: miranker@cs.yale.edu

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[1] While this seems to replace one mystery by another, we stress that doing so is a familiar process in scientific methodology. The gravitational and electromagnetic fields furnish examples in classical physics. These metaphysical constructs are unmediated and non-reducible. They are introduced to ‘explain’ gravitational and electro-magnetic phenomena.

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We shall take consciousness to be an emergent property of neural processing,[2] a special aspect of the information processing being performed in the brain.[3] Yet consciousness cannot be observed or measured objectively. It is, for this reason, what we call an internal property of matter. This aspect of consciousness which has defied a scientific (third-person, objective) approach towards its study is referred to as the *explanatory gap* in the consciousness studies literature. There is a place in science, namely quantum mechanics, where an internal property of matter plays a central role and is exploited to extraordinary benefit in the study of nature. The wave function or probability amplitude of QM, central to its methodology, has no existence in the reality of physics (Albert, 1993). It can neither be measured nor observed. This motivates the introduction of a quantum state description of a part of the brain, say, or more exactly, of the information processing in a part of the brain (see footnote 3). We shall see that such a description will allow us to use the unorthodox (the unobservable) features of QM to study consciousness in objective, scientific terms.

How and why could there be such a description of the brain? First it is not required that all parts of the brain be so constituted, nor is it required that a given part of the brain be exclusively so described, either at a fixed time or as time varies. A brain part may change dynamically by accretion and/or deletion of neurons. A part of the brain of interest could be composed of a large number of neurons (many millions) and an even larger number of synaptic connections (many billions). On some scale, we may regard the processing performed by such a system as stochastic. We shall hypothesize that the associated indeterminacy supports the quantum aspect of interest to us. We should ask: Why not characterize the system by classical probabilistic means? Why is it justified and what is the benefit of invoking the probability amplitude framework found in quantum mechanics? Motivated by the preceding discussion, we expect the benefit to be a deeper understanding of consciousness. The justification for formulating such an approach will be the results that redound and the experimental confirmation of such results.

Now consider two (or more) such parts of the brain[4] in interaction.[5] We shall polarize the roles of two such parts. One will be the (quantum-like) system, that we are discussing, and the second will play the role of a measuring apparatus, namely an observer of the information processing of the first part. (Of course, as in physics, the measuring apparatus may itself be taken as a quantum system.)

Now consider for the moment a classical system of electrical circuits, modeling the brain. Suppose that these circuits consist of two parts, where the first part

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[2] Even so, as we shall see, consciousness has a causal role with respect to the neural information being processed, and so, it is not simply an epiphenomenon of that processing.

[3] Information processing and, in particular, consciousness may be a feature of the entire nervous system, non-central as well as central. It may even depend on the non-neural corpus. So we should regard the use of the word brain here as somewhat euphemistic.

[4] While the relevant brain parts are separate in terms of organization, they could be quite intermeshed spatially. In an example discussed in Section III, the two parts comprise and share a single neuron.

[5] Again we stress the euphemistic use of the word brain. One of the so-called brain parts could very well be a sensory organ such as the retina or cochlea. Indeed as an anonymous referee has pointed out, one of these parts could be an element of external reality.

passes its output to become the input to the second. On the classical view, the second part is a passive receiver of information, in the sense that the flow of information and influence is unidirectional. On a quantum-like view of the two brain parts, the first part is the passive one. It is the second part, which takes an active role in order to acquire inputs, namely by making a measurement of the state of the first part. Continuing, we expect the second part to cause a change in the first part as it makes its measurement and takes its information. (Recall that the corresponding change in physics caused by a quantum measurement is an internal [i.e., non-observable] aspect of matter, being characterized by the collapse of the wave function of the state being measured; of the first part here.) This quantum view of the process of information flow is a kind of alteration of conventional causality, and it seems to confer on the pair of parts an augmented ontology. It is on this basis that we shall formulate a quantum state model of consciousness. With the quantum setting, we shall have an uncertainty principle, various kinds of non-locality, etc. (Penrose, 1989; Miranker, 1997).

Is consciousness epiphenomenal or causal? While the theory presented here does not settle this central question, it has one aspect that supports causality. This is the capacity of a quantum measuring apparatus (a brain part here) to cause a change in the system being measured. As we shall see, this change is the replacement of the pre measurement wave function representing the state of the system by its post measurement (its collapsed) state. In physics, the QM wave function has no known existence in reality. So any causality associated with the collapse of the wave function of physics must be found in the matter being characterized. In our theory, the quantum effects are not in the matter that comprises the brain, but are in the information, which is being processed, as we shall see. Conceivably this informational causality could be shown to be based on a material causality. This is a question that we defer to future work.

To proceed, we postulate the existence of a wave function (equivalently, a quantum state), ψ, for the brain (of the first part, Part I, say). Then we characterize the movement of information from the first to the second brain part (Part II, say) as resulting from a measurement (of the wave function) of the first part by the second. The wave function will thereupon collapse, and a definitive measurement emerges from an ensemble of possibilities (from the so-called potentia of Heisenberg; see footnote 10).

In QM, according to von Neumann (1955), Wigner (1961), etc., the causal agent of this collapse is the consciousness of a human observer (the one who makes the measurement). Here the causal agent is a physical process, namely the measurement of the state of a first brain part by a second. These two formulations of the causal agency are not necessarily different, since the observing part of the brain is, after all, a constituent or aspect of a human observer. We shall characterize this augmented view of information and its flow as consciousness.[6] For theories of consciousness based on more traditional QM considerations, see Globus (1998) and Stapp (1996).

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[6] These observations motivate a panpsychist view, since the object measured and the measuring device need not be brain parts. Indeed the parts might not even be neuronal. See Sheets-Johnstone (1998).

1. Outline

In Section II we introduce the model and explain how we attribute consciousness to the quantum measurement process. This comes from a duality between internal and external properties of matter arising in the quantum measurement process that we describe. Then it is suggested how subjective aspects of consciousness (in particular, qualia) arise as a scale of measurement effect. In Section III we show how quantum effects occur in the information processing performed by neuronal circuitry. In particular, we show how the processing of information by a McCulloch-Pitts neuron is characterized as a quantum measurement process. In Section IV we apply the theory of Section II and the techniques of Section III to develop a model of qualia. Analytic (mathematical) details are given in the appendix and in some of the footnotes.

II: The Model

Notice that the collapse of the quantum mechanical wave function is a fundamental process. That is, it is an unmediated and non-reducible property of nature. We shall say that the wave function knows that a measurement is being made, and that it responds to this information by collapsing. This is a fundamental form of awareness. Indeed, it is a primitive consciousness.[7] What is the composition of the putative form of awareness in the quantum model under consideration? We claim it is three things taken together: (i) that a measurement of information in one brain part by a second is being made, (ii) the value (i.e., the outcome) of that measurement, and (iii) the associated collapse of the wave function of the brain part being measured. Then we shall make the metaphysical hypothesis that the collapse of the wave function for a part of the brain (is not caused by consciousness as speculated in customary QM but) is the emergence of awareness/consciousness.[8]

In the present study, the measurement itself is what the observer (Part II of the brain) comes away with. So we take the value of the measurement, the input to the observing brain part, to be what we shall call the primal aspect of the measurement. We call this value the primal aspect because it is an external, i.e., an observable aspect of matter. The collapse of the wave function of Part I from ψ_I^- to ψ_I^+, say,[9] is a dual aspect of the measurement process (ψ_I^+ is an internal, i.e., non-observable aspect of matter). We use this terminology, because ψ_I^+ is an encoding of the value of the measurement as well. Indeed the value of the measurement could be extracted from ψ_I^+ by making a measurement of the latter (i.e., of Part I) immediately after the collapse in question. In QM performing a

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[7] We can expect that the manifestation of the collapse in the brain model here will play a role analogous to that of the unmediated and irreducible Hebb's law for synaptic change that furnishes the metaphysical synaptic level atom of awareness in an earlier study of consciousness by the author (Miranker, 2000).

[8] Whether this awareness is a primitive form or a more fully developed form of consciousness is a matter of the neuronal scale of Part I being measured, as we shall see.

[9] We use the superscript –/+ to denote the wave function immediately before/after collapse (measurement).

measurement corresponds to the application of an associated operator. Moreover the value of the measurement (say the number pointed to by the needle of a meter) can only be one of the eigenvalues λ_m of that operator. This duality within the quantum process of observation and collapse is characterized in Figure 1.

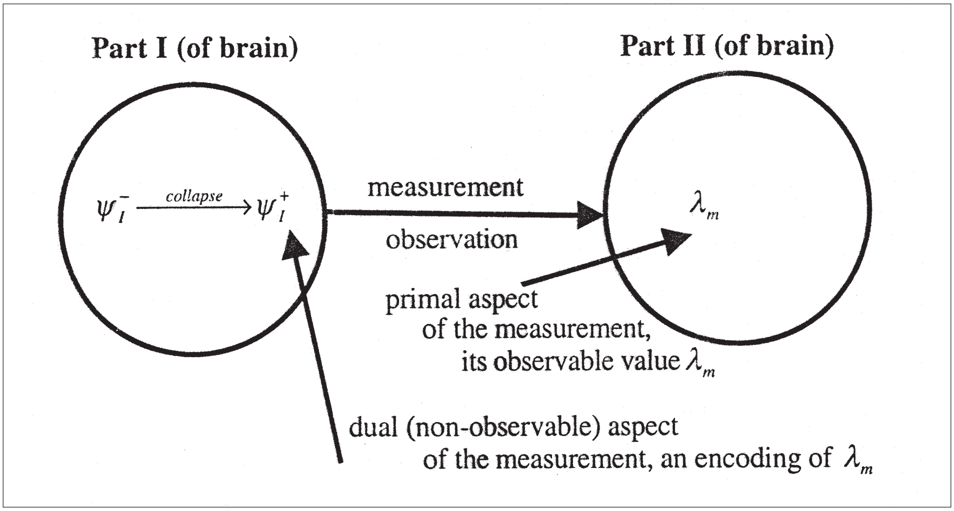

Figure 1. The duality between internal and external properties of matter

Then QM requires for the post measurement state (the collapsed state), that we have

$$\psi_I^- = \lambda_m \psi_m .$$

ψ_m is the eigenstate[10] of the measurement operator corresponding to its eigenvalue λ_m.

To clarify the primal/dual aspects of our quantum state model of consciousness, we formulate the following summary of the development so far.

Summary: Part II of the brain makes an observation/measurement of Part I. This causes the wave function of Part I, ψ_I^- to collapse to ψ_I^+, and the value of the measurement, λ_m, becomes the 'classical input' to Part II, or the value of the input, so-to-say. So the primal neural circuit information, λ_m, (a collection of frequencies, neural activities or action potentials, say) is passed on to Part II (or we may say is extracted by Part II from Part I by means of a measurement). This information is the conventional, observable encoding (an external property of matter) of the scene (an image, a colour, a sound, a pain, etc.) being processed in Part I. While this information is observable, for instance, by means of a set of

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[10] Here are some analytic details about this: Let $\left\{\lambda_i, \psi_i\right\}_1^n$ compose a so-called complete set of eigenelements of the measurement operator. Then for the pre-measurement state, we have $\psi_I^- = \sum_{i=1}^{n} a_i \psi_i$, for some constants a_i, i = 1, ... , n. The quantity λ_m emerges as the value of the measurement with probability $\left|a_m\right|^2 / \sum_{i=1}^{n} \left|a_i\right|^2, m = 1,\ldots,n$.

voltage probes, we stress that it is unconscious (i.e., it is not available as an internal experience to the possessor of the brain in question).

Now let us specify what in this process is described consciously. The state ψ_I^+ (an internal property of matter) is the quantum state of Part I, post measurement. ψ_I^+ is equal to the collapsed wave function $\lambda_m\psi_m$. Since the state ψ_I^+ is given explicitly in terms of λ_m, it encodes the primal scene (the conventional circuitry inputs to Part II) as well. So, ψ_I^+ is a dual state with respect to the property represented by the result of (the value of) the measurement λ_m. We shall say that the dual state (an internal property of matter) mirrors the primal state (an external property of matter). Along with the other features of the measurement process, the associated unmediated collapse of ψ_I^-, into ψ_I^+ is a manifestation of awareness or experience on the part of the measurement process. *Metaphorically we shall say that the wave function knows of the occurrence of the measurement process and expresses this experience of it by collapsing*. So the collapse/experiencing is taken to be the emergence of consciousness.[11] While the quantum measurement process is a part of the consciousness of the possessor of the brain in question, we stress that it is not observable to anyone else. (This is analogous to the non-observability of the wave function in quantum physics. There is current work [Hardy, 1992; Folman and Vager, 1995] attempting to change this.)

A winner-takes-all feature supplies an explanation for why we are conscious of only one experience at a time. It comes as a result of a competition (by means of inhibitory neuronal connections) among a set of possible brain Part IIs. Namely, a competition for what is to be measured in Part I (alternatively, which Part II gets to make a measurement), a competition for which experience is to spring into consciousness.

1. The atom of awareness, the awareness hierarchy, measurement scales, qualia

Key to explaining qualia is awareness/consciousness levels in the present model. These levels form a hierarchy embodied in the collapse process, the discrimination within the hierarchy being supplied by the scale on which the wave function ψ_I of Part I is viewed (i.e., on the scale on which the measurement by Part II is made). For instance, Part II might focus on the wave function of a synapse (only), perhaps the finest scale, and the collapse of such a *primitive wave function* could be taken as the *atom of awareness* (the primitive form of consciousness) in this quantum model. Or Part II might focus on the wave function of an entire neuron, and the collapse of such a wave function could be the neuronal level awareness (i.e., consciousness at a neuronal level) in the quantum model, etc. Naturally the wave function of a larger collection, say a cell assembly, includes all aspects of (the wave function of) its parts (as in physics). So with the collapse of the wave function of a cell assembly say, we have the collapse of all wave function

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[11] While this metaphor may seem novel, it has been used implicitly in quantum mechanics proper since the 1920s. Newton uses the metaphor in classical physics in the *Principia* where he proposes that the water in a bucket knows if the bucket is rotating or not. (This as quoted by Gribben, 1995, p. 227.) What is novel here is the replacement of consciousness as the causal agent of the collapse by the attribution of consciousness to the collapse itself.

constituents, down to the synaptic level.[12] *The attribution of consciousness to the collapse of the wave function of a neuronal assembly is based on (is a ramification of) the metaphysics (namely on the 'knowing of' the occurrence of the measurement) attributed to the atomic constituents of this awareness hierarchy.*[13] For instance, if a brain part is processing the colour red (of course, as unconscious, but externally observable information), the quale red is experienced, because the movement of that information from that brain part corresponds to an awareness (i.e., to a measurement and collapse) of a higher, complex form in this awareness hierarchy. In addition to qualia, we expect that other inner, subjective aspects of consciousness such as the notion of self, free will, feelings, etc., will be explained by means of ramifications of the patterning of collapse within the awareness hierarchy. Our model provides a ground for such a programme. In Section IV we formalize these ideas with a specific quantum model of qualia.

III: Quantum Effects In Neuronal Information Processing

Now we return to the issue that quantum effects occur in neuronal circuitry, in brain parts. Such effects can occur in at least two ways.

A. Quantum effects in the physics of the matter comprising neuronal structures
B. Quantum effects in the information processing performed by the neurons

A. The possibility of quantum effects in neuronal matter is discussed in Penrose (1989; 1994; 1997) and Hameroff and Penrose (1996). They place these effects in the microtubules that comprise the cyto-skeleton of the neurons. The microtubule walls are alleged to furnish the isolation needed for the subtle quantum effects to occur.[14] The tubulin dimers (about one million per neuron) that compose the microtubule walls are taken to be the units that encode the quantum states. Indeed the polarized structure of those dimers suggests to Hameroff and Penrose the possibility of spin-like states.

B. In Miranker (1997) it is shown that the processing of information in a computer (in particular, performing the computer arithmetic) can be represented as a quantum measurement process.

Using the development in B as motivation, we shall show how neuronal information processing itself may be represented as a quantum process. Note that the quantum effects we shall appeal to are in the information processing and not directly in the material of the neurons as in A, say. In this section we give a

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[12] The way the collapsing unfolds is likely to be subject to neuronal inhibitory and excitatory effects. Details of the patterns of this hierarchical collapse process must be deferred to future study.

[13] In an earlier study of consciousness (Miranker, 2000), we also have an awareness hierarchy, starting with the synaptic level (the Hebbian dynamics) atom of awareness (a primitive form of consciousness), then proceeding to the neuronal level awareness, and finally to the awareness/information state I of a cell assembly. The importance of the awareness hierarchy is that it showed how step by step, starting with the primitive level, awareness at the cell assembly level comes about. The latter, of course, is taken to correspond to the experiencing of a quale.

[14] Without isolation, the QM wave function would spontaneously collapse, compromising its utility.

descriptive summary of this information processing quantum process, the details of which are presented in the appendix.

For reasons of clarity we consider the basic McCulloch-Pitts neuron with n input synapses (see the appendix for details). We suppose that an input synapse (like any instrument, natural or artificial) cannot discriminate between inputs to it that are too close in value. To model this we introduce a screen of values called R, a discrete set of numbers that form the totality of (discriminable) synaptic values. These are exactly like the values on a digital meter, so that this arrangement is completely relevant to actual measurement devices. In computer terminology, such a set of values is called a screen of floating-point numbers.

Let us denote the n synaptic inputs by the vector $x = (x_1,...,x_n)$. Each synaptic input is the weighted product, (synaptic strength) x (input to that synapse). We introduce a wave function or state corresponding to the inputs, namely

$$\psi(\xi) = \sum_{k=1}^{n} B_k e^{i\frac{\xi}{h}}.$$

Each $B_k = B_k(\xi)$, a function of ξ, is zero everywhere except on a certain interval having the number x_k as its midpoint. Also the value of B_k on that interval is a specified constant that depends on the input x_k. The neuron sums the individual synaptic inputs and fires (or not) depending on a customary threshold process (see the appendix for details).

In Miranker (1997) a summation operator, called S, is explicitly derived (see the appendix for its form). In terms of this operator, the quantum measurement (corresponding to the weighted summation of inputs performed by the McCulloch-Pitts neuron), denoted by the (customary QM) symbol $(\psi, S\psi)$, has the following value:

$$(\psi, S\psi) = \sum_{i=1}^{n} x_i + \mathrm{L}$$

That is, the quantum measurement is indeed the required weighted sum plus a small error.

So when Part II of the brain is taken to correspond to the case of a single neuron (here a McCulloch-Pitts neuron), the operator S represents the action of that neuron making a quantum style measurement of Part I that mirrors the neuron's conventional circuit input weighted summation process. Part I is the neural assembly that in the conventional sense of neural circuitry supplies the totality of required input activities to that McCulloch-Pitts neuron comprising Part II. Equivalently, Part I consists of the input synapses of the single neuron that comprises Part II in question. On this latter view, Parts I and II share aspects of the same neuron. (That is, they share both the physical material composing this neuron as well as the information that neuron is processing.)

1. Determinacy of the operator S

In quantum physics, measurement (the act of applying an appropriate operator) is a random process. The outcome of the measuring process can be any one of the eigenvalues of that operator, each one occurring with a certain probability as specified by the quantum theory (see footnote 10). This is not the case for the operator *S*, since the result of applying *S* is the unique value (a deterministic result) of the sum in question.

The determinacy of the quantum measurement process (so-called strong determinism) is a feature proposed by Roger Penrose (1989, p. 432) in his proposals toward a quantum theory for consciousness. He arrives at this position starting with the Gödel/Turing incompleteness theorem. Penrose claims that mathematical understanding (a form of mind) is not algorithmic (is not Turing computable) according to this theorem. Penrose asserts, 'If one has strong determinism in the measurement process . . . the mathematical scheme which governs the structure of the universe would probably have to be nonalgorithmic.' For this reason, he continues, consciousness is potentially characterizable by that nonalgorithmic mathematics.

IV: Qualia

As an application of the theory of consciousness presented here, we develop a model of qualia. For definiteness, consider audition. A mechanical disturbance in the air impinges on the eardrum and is transduced into electrochemical signals in the cochlea. These signals are then processed as primal quantities (e.g., as voltages in the nervous system that are externally measurable). A quantum measurement process characterizes (mirrors) this. In particular, an operator Q called the (phenomenal) sound operator is invoked by a neural assembly instantiated to make that measurement. (This assembly is a Part II.) When it acts, phenomenal sound is created. There is no change in the primal neural processing (in the physical circuitry), which is augmented by the appearance of the quale sound. There is a competition among neural assemblies for making the measurement with the winner producing the phenomenal result. The competition might be in terms of the inputs, the outputs, or both. Since *a quale is not a thing* (it is not a primal quantity such as a voltage), we do not attribute a location to it. The same picture prevails for other sensory inputs and for feelings as well.

Let *W* denote the operator corresponding to the synaptic weights of the entire neural assembly (the Part II) in question. *W* is a matrix composed of these synaptic weights. More specifically, it is a matrix composed of those weights corresponding to exogenous inputs to the assembly. Using the summation operator *S* introduced in Section III, we form the product *SW*. This product denotes the weighted sum operator, namely the operator that converts all of the assembly's exogenous inputs into the weighted sums that are the total exogenous inputs to the neurons in the assembly that receives the exogenous inputs in question (Part II). Let ψ denote the wave function[15] corresponding to those exogenous inputs. (The neural circuitry that supplies these inputs represents a Part I.) The quale will correspond to the quantum measurement operator Q. Then the value of the measurement is given by the expression $(\psi, Q\psi)$, where[16]

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[15] This will in fact be a vector of wave functions.

[16] Here are some analytical details about this: The QM expression $(\psi, Q\psi)$ is a vector of inner products where, in particular,

$$Q = W^T SW.$$

So the neural assembly (Part II) is specified for the measurement in question. Specification means that the synaptic weights corresponding to the operator W are developed (through learning, training, perhaps also genetically) to produce the quale.

Appendix

In this appendix we supplement the development in Section III, supplying the analytic details.

For reasons of clarity we take as our model the basic McCulloch-Pitts neuron with n input synapses. Let $w = (w_1,...,w_n)$ be the vector of synaptic weights, and let $\nu_a = (\nu_1{}^a,..., \nu_{\mathrm{n}}{}^a)$ be the vector of afferent activity. We take the neuronal output, ν^e, to be the value of a gain function, g, (with threshold) applied to the total input. In particular,

$$\nu^e = g(u - \theta) ,$$

where the total neuronal input u is a sum of the n weighted synaptic inputs[17]

$$u = \sum_{k=1}^{n} w_k \nu_k^a,$$

and θ is a threshold. In the McCulloch-Pitts case, g is a simple step function,

$$g(x) = \begin{cases} 1, x \geq 0, \\ 1, x < 0. \end{cases}.$$

Now we suppose that an afferent synapse (like any instrument, natural or artificial) cannot discriminate between inputs to it that are too close in value. To model this we introduce a screen of values called R, a discrete set of numbers, which form the totality of possible synaptic values. These are exactly like the values on a digital meter, so that this arrangement is completely relevant to actual measurement devices. In computer terminology, such a set of values is called a screen of floating-point numbers with base b and mantissa μ. If x is such a screen number, it has the form

$$x = \mu b^e (= \mu_x b^{e_x}),$$

where the exponent e is an integer lying in some specified range, say $e \in [e_{\min}, e_{\max}]$. These features (including the length of the mantissa) of the screen are fixed by the quality of the measuring device (the neuron or the computer, as the case may be). In the terminology of quantum physics, such features depend as

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$$\begin{aligned} (\psi, Q\psi) &= (W\psi, S\psi), \\ &= (\psi, W^T SW\psi), \end{aligned}$$

We deduce the indicated form of the quale operator Q from the second equation here. See the appendix for the explicit form of the summation operator S.

[17] Neuronal information is frequency encoded. The amplitudes ν^a and ν^e of the McCulloch-Pitts model represent the values of those frequencies.

well on the spectrum of the operator representing the measurement, since the outcome of a measurement can only be one of those spectral values.

Following Miranker (1997) we introduce a wave function or state corresponding to a vector $x = (x_1, ..., x_n)$ where each $x_k, k = 1, ..., n$, is a screen number (a number in R). The wave function is

$$\psi(\xi) = \sum_{k=1}^{n} B_k e^{i\frac{\xi}{h}}.$$

$B_k(\xi)$ is a step function of ξ. It is zero except on a certain interval $[m_p(x_k), m_s(x_k)]$, containing x_k. Since ψ is to be a probability amplitude, normalization (the total probability must be unity) requires that $B_k = [m_p(x_k) - m_s(x_k)]^{-1/2}$ on that interval. The interval's right endpoint $m_s(x_k)$ is the midpoint of the screen number x_k and its successor screen number. The latter is the smallest screen number larger than x_k. The interval's left endpoint $m_p(x_k)$ is defined analogously, being the midpoint of x_k and its predecessor screen number. We note that

$$x_k = [m_s(x_k) - m_p(x_k)]/2,$$

when the screen is (locally) uniform, which we shall suppose is the case.

A quantum observation or measurement corresponds to an operator U and has as value the following inner product:

$$(\psi, U\psi) = \int \psi(U\psi)^* \, d\xi.$$

(The value is a stochastic choice, corresponding to the collapse of the wave function, made from a collection of possibilities associated with the inner product shown here. See footnote 10.) In the present case, we shall see that a deterministic process replaces this stochastic aspect (compare Section III.1).

Now we identify the weighted input $s_k \nu_k^a$ at the k-th synapse as the screen number x_k. We identify (mirror) the total neuronal input with the wave function $\psi(\xi)$ shown above. The neuron sums the individual synaptic inputs and passes the result through the threshold gain function, g, as we have noted in our discussion of the McCulloch-Pitts model.

Let us denote the quantum summation process by the operator S. In Miranker (1997) this summation operator is shown to be defined as follows:

$$S\psi(\xi) = \mathrm{h} \int_{-\infty}^{\xi} \varsigma \psi(\varsigma) d\varsigma.$$

Indeed, it is also shown there that

$$(\psi, S\psi) = \sum_{k=1}^{n} [m_s(x_k) - m_p(x_k)] + \mathrm{L}$$

$$= \sum_{k=1}^{n} x_k + \mathrm{L}\,.$$

That is, the inner product representing the value of a quantum summation measurement is the required sum plus a small error.[18] Let a denote the value of this inner product, i.e., of the quantum measurement sum. (Recall that a is a number in the screen R of possible [weighted synaptic] values.) Note that the post-measurement (collapsed) wave function is $\psi_I^+ = B(\xi;a)e^{i\frac{\xi}{\hbar}}$. Here $B(\xi;a)$ is a step function of ξ, having the value $[m_s(a) - m_p(a)]^{-1/2}$ on the interval $[m_p(a), m_s(a)]$ and the value zero otherwise.

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[18] A quantum style operator denoted by Θ could also mirror the action of the gain function. In particular, we have

$$\Theta B_k e^{i\frac{\xi}{\hbar}} = B_k e^{i\frac{\xi}{\hbar}} \begin{cases} 1, & x_k \geq \theta, \\ 0, & x_k < \theta. \end{cases}$$

Since Θ is a deterministic nonlinear operator, this represents a change from conventional quantum physics where operators representing measurements are linear and Hermitian.