Shadows of the mind
Roger Penrose

1 Consciousness and computation

1.1 Mind and Science. We are a long way from scientifically understanding the mind but it is possible, it is not computational and here is a theory to begin with.

1.2 Can Robots save this Troubled World? Computer power is increasing exponentially and some argue that they will surpass humans.

1.3 The A, B, C, D of computation and conscious thinking.

A) All thinking is computation; in particular, feelings of conscious awareness are evoked merely by the carrying out of appropriate computations.
B) Awareness is a feature of the brains physical action; and whereas any physical action can be simulated computationally, computational simulation cannot by itself evoke awareness.
C) Appropriate physical action of the brain evokes awareness, but this physical action cannot be properly simulated computationally.
D) Awareness cannon be explained by physical, computational or any other scientific terms.

A. Serious possibility but false
B. Common scientific common sense
C. Argument is for this view
D. Rejected as all can be addressed by science.

1.4 Physicalism vs. Mentalism. Terms will not be used as they are unclear across A-D

1.5 Computation; top-down and bottom-up procedures. Top-down and bottom-up are computationally the same as are parallel and serial. They all run on a Turing machine.

1.6 Does viewpoint C violate the Church-Turing thesis? No.

1.7 Chaos. Chaotic systems are deterministic but so sensitive to initial conditions and with so many variables as to be uncomputable in practice (but not theory)

1.8 Analogue computation. Not relevant because we are considering Turing machines here. There may be something fundamentally different with analogue but it is unlikely.

1.9 what kind of action could be non-computational? Examples given of problems without an algorithmic solution: Diophantine equations (simultaneous equations with an integer soln) and the tiling problem (will these tiles cover a plane completely?)

1.10 What of the future? A&B will be superseded by robots. C has a poorly understood chance. D will remain superior.

1.11 Can computers have rights and responsibilities? A - yes. B - no but how do you tell. C&D no.

1.12 Awareness, understanding, consciousness, intelligence. Clarification of terms. (genuine) intelligence requires understanding requires awareness. AI proponents use the terms differently. Awareness is the passive aspect of consciousness; free will is the active.

1.13 John Searle's argument. The man in the room manipulating Chinese symbols does not understand the content, therefore a computer doesn't understand the content. Persuasive but not conclusive.

1.14 Some difficulties with the computational model. Refuting A. How must an algorithm be enacted to evoke awareness? Is writing it down sufficient? How complicated must the algorithm be?

1.15 Do limitations of present-day AI provide a case for V? AI and computers have along way to go yet but we will discuss basic principals here which will not be altered by speed or memory. Understanding is in the writing of the algorithm not the running.

1.16 The argument from Godel's theorem. Strengthened from ENM.

1.17 Platonism or mysticism? No need to accept D but C Implies Platonism.

1.18 What is the relevance of mathematical understanding? Because math is rigorous and it attacks A on their home ground.

1.19 What has Godel's theorem to do with common-sense behaviour? We easily understand the concept of natural numbers and their inherent infinite.

1.20 Mental visualization and virtual reality. Models (which mirror) of reality are distinct from *understanding* physical reality.

1.21 Is mathematical imagination non-computational? Simulation requires human understanding. We use a non-computable capability to do this.

2 The Godelian case

2.1 Godel's theorem and Turing machines. Godel: No formal system of sound mathematical rules of proof can ever suffice, even in principal, to establish all the true propositions of ordinary arithmetic. Therefore Penrose: human understanding and insight cannot be reduced to any set of computational rules.

2.2 Computations. Example: find natural number that is not the sum of three square numbers.

2.3 Non-stopping computations Example: find a natural number that is not the sum of four square numbers. (proven false by Lagrange)
Example: find the odd number that is the sum of two even numbers. (false by common sense)
Example: find the even number greater than 2 that is not the sum of two prime numbers. (unproven)

2.4 How do we decide that some computations do not stop? Example: find a sum of successive hexagonal numbers, starting from 1, that is not a cube.(visualise as a 3-D cube rather than a flat hexagon)

2.5 Families of computations; the Godel-Turing conclusion €. € Human mathematicians are not using a knowably sound algorithm in order to ascertain mathematical truth.

2.6 Possible technical objections to €. Q1-9 deal largely with questions based on a poor understanding of the argument as stated.

2.7 Some deeper mathematical considerations. Formal mathematical systems were developed to avoid any ambiguities introduced by infinite sets (Bertram Russell). Godel proved the formalists desire to have a system which was both consistent (No statement is both true and false) and complete (no undecidable statements)

2.8 The condition of w-consistency

2.9 Formal systems and algorithmic proof 2.10 Further possible technical objections to €

Appendix A: An explicit Godelizing Turing machine

3 The case for non-computability in mathematical thought

3.1 What did Godel and Turing think?

3.2 Could an unsound algorithm knowably simulate mathematical understanding?

3.3 Could a knowable algorithm unknowably simulate mathematical understanding?

3.4 Do mathematicians unwittingly use an unsound algorithm?

3.5 Can an algorithm be unknowable?

3.6 Natural selection or an act of God?

3.7 One algorithm or many?

3.8 Natural selection of unworldly esoteric mathematicians

3.9 Learning algorithms

3.10 May the environment provide a non-algorithmic external factor?

3.11 How can a robot learn?

3.12 Can a robot attain `firm mathematical beliefs'?

3.13 Mechanisms underlying robot mathematics

3.14 The basic contradiction

3.15 Ways that the contradiction might be averted

3.16 Does the robot need to believe in M?

3.17 Robot errors and robot `meanings'?

3.18 How to incorporate randomness-ensembles of robot activity 3.19 The removal of erroneous *-assertions

3.20 Only finitely many *,-assertions need be considered

3.21 Adequacy of safeguards?

3.22 Can chaos save the computational model of mind?

3.23 Reductio ad absurdum - a fantasy dialogue

3.24 Have we been using paradoxical reasoning?

3.25 Complication in mathematical proofs

3.26 Computational breaking of loops

3.27 Top-down or bottom-up computational mathematics?

3.28 Conclusions

Part II: What New Physics We Need to Understand the Mind.

The Quest for a Non-Computational Physics of Mind

4 Does mind have a place in classical physics?

4.1 The mind and physical laws. It may be unsettling to consider that we might be constrained by precise mathematical physical laws but duality is very difficult to entertain. Some say that referring to the mind as a different type of substance obeying different laws is a category error. However $E=MC^2$ and entropy are two examples in physics where two apparently different categories have a clear relationship.

4.2 Computability and chaos in the physics of today. The precision and scope of physical laws as presently understood is extraordinary. Classical systems (including chaotic systems) can be simulated with discrete computation provided that the parameters can be digitised to sufficient accuracy. Often we are satisfied with typical behaviour rather than actual behaviour. Just possibly analogue is different, but probably not. In quantum physics there is additional freedom of a completely random nature, over and above the deterministic (and computable) behaviour.

4.3 Consciousness: new physics or `emergent phenomenon'? Why does consciousness only occur in brains? It cannot just be complexity. How has consciousness eluded physics so far?

4.4 The Einstein tilt. Newton described gravity in 1687. Maxwell described electric and magnetic fields in 1865. Bohr, Heisenburg, Schrodinger and Dirac introduced quantum theory in 1913-26. Einstein re-examined Newtonian gravity in 1915. Gravity is not just a residual of the other stronger forces because it is the only force that influences the causal relationships between space-time events. Special relativity treats Minkowski space in the absence of gravity where the light cones are arranged uniformly. General relativity introduces gravity which tilts the light cones (or varies the speed of light from place to place). It is not merely refraction because in some extreme circumstances th tilt can exceed 90°. This can be observed with gravitational lensing. This is simply a demonstration that a fundamentally new property can go unobserved only to be discovered later.

4. Computation and physics. When a neutron star collapses it maintains its angular momentum and so rotates very quickly. Particles trapped in the intense surrounding magnetic field radiate violently when their speed approaches closely the speed of light. The rotational speed is remarkably precise (10^{-12} sec p.a.) and agrees precisely with general relativity. Gravitational radiation is another example to an accuracy of 10^{-14}. Calculated simulations with two gravitational bodies agree with General Relativity to high accuracy. Calculations with multiple or many bodies based on Newtonian physics are also accurate but for the typical evolution of a system rather than the actual evolution. An extreme example is a Newtonian gas where particles are treated in a statistical way with the 2nd law of thermodynamics ensuring that the system evolves in a typical, not atypical, way. Thermal equilibrium refers to an ensemble of states (not one) that appear identical in a macroscopic sense. The most pure and precisely tested example of thermodynamic behaviour – the thermal equilibrium known as black-body – cannot be treated entirely classically, but the precision is extraordinary.

Modelling biological systems is unlikely to be as precise and involve chemical reactions which involve quantum theory........

5 Structure of the quantum world

5.1 Quantum theory: puzzle and paradox. Quantum theory provides a superb description of physical reality on a small scale but it contains many mysteries. Z-mysteries are genuinely puzzling but directly experimentally supported facts about the world. X-mysteries are paradoxical implications of the quantum formalisations which are very difficult to believe are actually true of the world. Random elements along cannot provide the type of non-computability required to understand mentality.

5.2 The Elitzur-Vaidman bomb-testing problem. In a classical world is is impossible to quality test a photon-sensitive trigger mechanism on a bomb because all testing is necessarily destructive testing. It is possible in a quantum world using counter factuals.

5.3 Magic dodecahedra. A product of Quinisential Trinkets which guarantees that two widely separated dodecahedron will behave as if they are classically influenced where no such classical connection is possible. Each contains a particle with spin $^3/_2$ with a combined spin of 0.

5.4 Experimental status of EPR-type Z-mysteries. The phenomenon of quantum entanglement was first noticed by Erwin Schrodinger in 1935. In 1966 John Bell opened the way to experimentation with the Bell inequalities between the joint probabilities of various spin measurements which should hold in classical physics but be violated by quantum physics.

5.5 Quantum theory's bedrock: a history extraordinary. Gerolamo Cardano 1501-1576 developed probability theory, complex numbers and host of other inventions. $i=\sqrt{-1}$

5.6 The basic rules of quantum theory. The classical laws of Newton, Maxwell and Einstein hold at a typically larger scale than the quantum level which is concerned with very tiny differences in energy. There need not be any physical distinction between the classical and quantum levels. An electron can have any one of a number of possible states in which, in some clear sense, it occupies both locations simultaneously. The notation $|A\rangle$ indicated the state in which an electron occupies position A. Multiple possible states is written as ψ $|\psi\rangle = w|A\rangle + z|B\rangle$ where the weighting factors w and z are complex numbers (at least one is non). Complex numbers provide a mathematically precise and probability-free description of the quantum level of activity.

5.7 Unitary evolution U. U will denote the Unitary evolution described by the Schrodinger equation, which provides the rate of change with respect to time of the *quantum state* or *wavefunction*. The quantum state (or state vector) $|\psi\rangle = w|A\rangle + z|B\rangle$ is the linear supposition of the two states $|A\rangle$ and $|B\rangle$. Only the ratios of the complex weighting factors have significance. $|\psi\rangle$ is linear in the sense that evolution after time t (→) is linear:

$$\textit{If}\ |\psi\rangle \rightarrow |\psi'\rangle \ \text{and}\ |\theta\rangle \rightarrow |\theta'\rangle$$
$$\textit{then}\ w|\psi\rangle + z|\theta\rangle \rightarrow w|\psi'\rangle + z|\theta'\rangle$$
$$\textit{would also hold.}$$

Example: a photon passing thru a 50% silvered mirror evolves according to $|A\rangle \rightarrow |B\rangle + i|C\rangle$ where the factor "i" arises because of a net phase shift by a quarter of a wavelength (ignoring a time-dependent oscillatory factor and assuming normalisation)

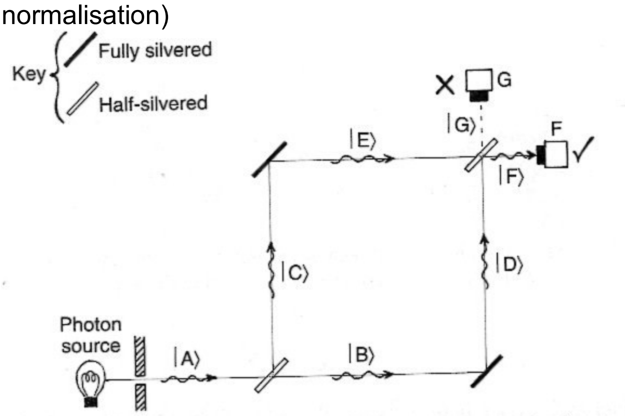


Fig. 5.12. The two parts of the photon state are brought together by two fully silvered mirrors, so as to encounter each other at a final half-silvered mirror. They interfere in such a way that the entire state emerges in state |F⟩, and the detector at G cannot receive the photon. (Mach–Zehnder interferometer.)

The final state in this example is $-2|F\rangle$. The multiplying factor of -2 plays no physical role.

5.8 State-vector reduction R. R denotes the state-vector reduction or collapse of the wavefunction which occurs when the superposed quantum-level state "jumps" to a description where one or other of the classical-level alternatives takes place. R is the basic X-mystery of quantum theory.

When the superposed state $w|F\rangle + z|G\rangle$ encounters a detector, the probability of the classical-level alternatives is given by $|w|^2 : |z|^2$ which are the squared moduli of the complex numbers w and z. Where $z = x + iy$ the squared moduli $|z|^2 = x^2 + y^2 = (x+iy)(x-iy) = z\bar{z}$. In the example; if the photon is not absorbed by the obstruction then state $-|E\rangle \rightarrow -|F\rangle - i|G\rangle$

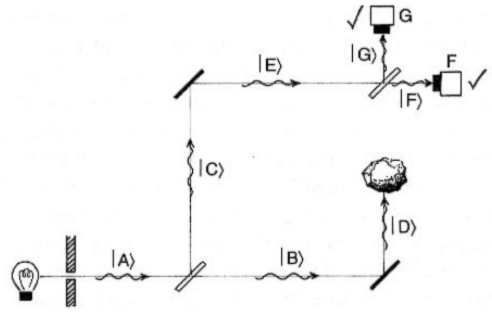


Fig. 5.13. If an obstruction is placed in the beam |D⟩, then it becomes possible for the detector at G to register the arrival of the photon (when the obstruction does *not* absorb the photon!).

with probabilities $|-1|^2 : |-i|^2 = 1 : 1$

5.9 Solution of the Elitzur-Vaidman bomb-testing problem. Place the photon-sensitive trigger of the bomb at the position of the obstruction in the example. If the trigger is faulty, and the mechanism is jammed, then $|G\rangle$ cannot occur. If the bomb is active it will either explode (on receipt of a photon) 50% or $|F\rangle$ 25% or $|G\rangle$ 25% will occur. If the bomb does not explode and $|G\rangle$ occurs then the bomb is active. Those that result in $|F\rangle$ can be retested with the ultimate result that ⅓ of the active bomb will be confirmed active and unexploded ($\frac{1}{4}+\frac{1}{16}+\frac{1}{64}+\ldots=\frac{1}{3}$)

5.10 Quantum theory of spin; the Riemann sphere. Spin is an intrinsic property of particles. Angular momentum of a classical object is dominated by the orbiting motion of all of the particles around a single axis. Spin of a fundamental particle always has the same magnitude but the direction of spin may vary. The magnitude of spin is described by a non-negative integer or half-integer multiple of Dirac's constant $\hbar = h/2\pi$ where h is Planck's constant.

The Riemann sphere describes, in an abstract geometrical way, the space of physically distinguishable states that can be built up, by quantum linear supposition, from any two distinct quantum states.

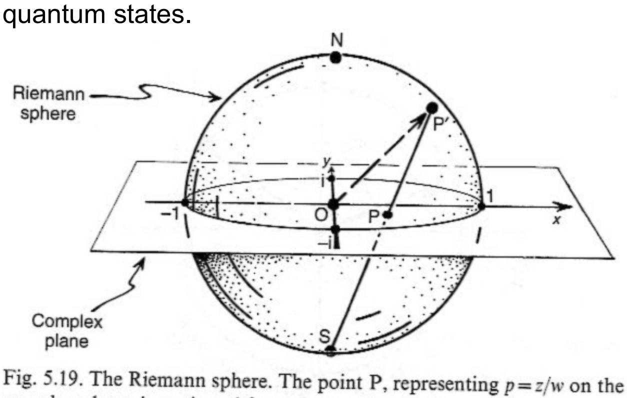


Fig. 5.19. The Riemann sphere. The point P, representing $p = z/w$ on the complex plane, is projected from the south pole S to a point, P′ on the sphere. The direction OP, out from the sphere's centre O, is the direction of spin for the general spin 1/2 state of Fig. 5.15.

For example: For spin½, all the states of spin are linear superpositions of just two states, say the right-handed spin about the upward vertical, written $|\uparrow\rangle$, or right-handed spin about the downward vertical, written $|\downarrow\rangle$. The general state of spin is $|\psi\rangle = w|\uparrow\rangle + z|\downarrow\rangle$ which represents the state of spin, of magnitude $\frac{1}{2}\hbar$, which is right handed about the axis that points in the direction of the point on the Riemann sphere P' representing P, the ratio p=z/w.

States of spin higher than ½ get more complicated. When measured in units of $\frac{1}{2}\hbar$ the amount of spin in this direction has one of the values n, n-, n-4,..., 2-n, -n. The different possible states of spin ½ n are the complex-number superpositions of these possibilities.

$$|\uparrow\uparrow\uparrow\ldots\uparrow\rangle, |\downarrow\uparrow\uparrow\ldots\uparrow\rangle, |\downarrow\downarrow\uparrow\ldots\uparrow\rangle, \ldots, |\downarrow\downarrow\downarrow\ldots\downarrow\rangle$$

We can think of each arrow providing $\frac{1}{2}\hbar$ of spin in the upward direction. The larger the magnitude of the spin the more directions there are involved.

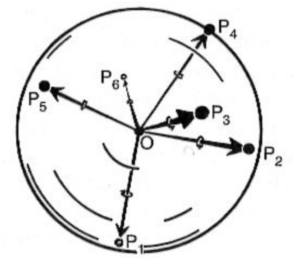


Fig. 5.21. The Majorana description of the general state of spin $\frac{1}{2}n$ is as an unordered set of n points $P_1, P_2, \ldots P_n$ on the Riemann sphere, where each point may be thought of as an element of spin $\frac{1}{2}$ directed outwards from the centre to the point in question.

The correspondence principle in quantum theory asserts, in effect, that when physical quantities get large, then it is possible for the system to behave in a way that closely approximates classical behaviour.

5.11 Position and momentum of a particle. Heisenbergs uncertainty principle provides limits to how clearly defined can be position and momentum simultaneously. The states of well-defined momentum have an oscillatory spacial behaviour in the direction of motion. Here oscillatory refers to pure phases that circle about the origin at a constant rate – giving a frequency v that is proportional to a particles energy E, in accordance with Plank's formula E=hv.

5.12 Hilbert space. The family of all possible states of a quantum system constitute what is known as a Hilbert space. Hilbert space is a complex vector space; possibly infinite (but two dimensional for spin½). Quantum state vector $|\psi\rangle = u|\psi\rangle$, so a physical situation is represent by a ray rather than just a point in Hilbert Space. However, because the Hilbert space is complex the ray is really an entire complex plane. The Hermitian scalar product (or inner product) can be applied to any two Hilbert-space vectors to produce a single complex number. This enables the expression of the squared length and the orthogonality of a Hilbert-space vectors. Two vectors are orthogonal (independent) when the scalar product = 0. Orthogonal states will be preserved (remain orthogonal) if each is evolved, according to U, over the same period of time. The scalar product satisfies:

$$\langle\bar{\psi}|\bar{\Phi}\rangle = \langle\psi|\Phi\rangle$$
$$\langle\psi|(|\Phi\rangle + |X\rangle) = \langle\psi|\Phi\rangle + \langle\psi|X\rangle,$$
$$(z\langle\psi|)|\Phi\rangle = z\langle\psi|\Phi\rangle,$$
$$\langle\psi|\psi\rangle > 0 \text{ unless } |\psi\rangle = 0$$

It is important to note a $|\psi\rangle$ and $|\Phi\rangle$ are orthogonal iff $\langle\psi|\Phi\rangle = 0$ and that $\langle\psi|\psi\rangle$ is the squared length of $|\psi\rangle$.

5.13 The Hilbert-space description of R. When a yes/no measurement is made, the equipment can register a positive YES or a NO if it fails to register; which includes the possibility that the NO alternative might be a null measurement. The null measurement is indeed a measurement and causes the state to "jump" into an orthogonal state. More complicated measurements can be built up from yes/no measurements. This "jumping" is the most puzzling aspect of quantum theory. The projection postulate asserts that a YES answer ascertains that the quantum state is – or has jumped to – some particular state $|\psi\rangle$ (or to some non-zero multiple $u|\psi\rangle$). That is the physical state is one particular thing. A NO measurement projects the state to something that is orthogonal to . $|\psi\rangle$ The state vector can be written as $|\psi\rangle = z|\alpha\rangle + |X\rangle$ Probabilities of the outcomes are assigned by demanding that $|\alpha\rangle$ is a unit vector and choosing some unit vector in the direction of $|X\rangle$.

5.14 Commuting measurements. If the ordering of the measurements plays no role what-so-ever then we say that they commute.

5.15 The quantum-mechanical `and'. The tensor product or outer product represents combining the quantum states of two different particles (as opposed the the superposition of a single particle).

$$(z|\alpha\rangle)|\beta\rangle = z(|\alpha\rangle|\beta\rangle) \;=\; |\alpha\rangle(z|\beta\rangle)$$
$$(|\alpha\rangle + |\gamma\rangle)|\beta\rangle = |\alpha\rangle|\beta\rangle + |\gamma\rangle|\beta\rangle$$
$$|\alpha\rangle(|\beta\rangle + |\gamma\rangle) = |\alpha\rangle|\beta\rangle + |\alpha\rangle|\gamma\rangle$$
$$(|\alpha\rangle|\beta\rangle)|\gamma\rangle = |\gamma\rangle(|\beta\rangle|\gamma\rangle)$$

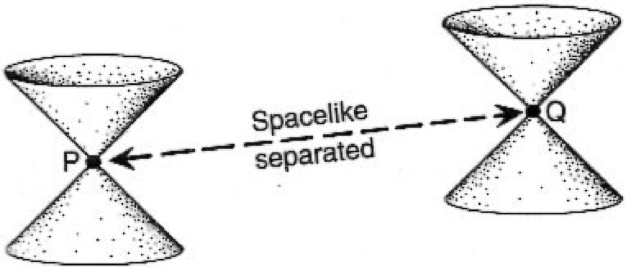
Note that in quantum physics the Grassmann product is actually used rather than the tensor product such that:

$$tensor: \quad |\alpha\rangle|\beta\rangle = |\beta\rangle|\alpha\rangle$$
$$Grassmann: \quad |\alpha\rangle|\beta\rangle = \pm|\beta\rangle|\alpha\rangle$$

where the '-' sign occurs precisely when both the states have an odd number of particles whose spin is not an integer. Linearity holds during evolution, as you would expect for non-interacting particles (quite different in this sense to superposition)

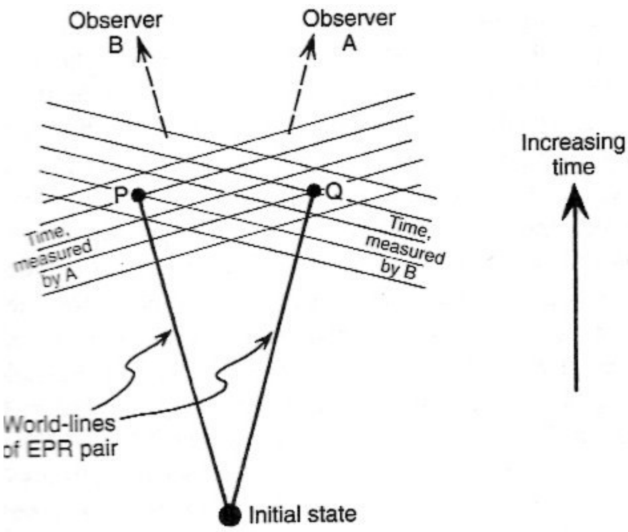
5.16 Orthogonality of product states. Note that the necessity of using the Grassmann product rather that the pure tensor product arises because two orthogonal states do not remain orthogonal on the inclusion of an additional state. Technically, even the state of a photon on the moon is not completely separate from one on earth. This effect is extremely small but has been used to measure the diameter of nearby stars by the boson property interrelating photons reaching the earth from the opposite sides of the star.

5.17 Quantum entanglement. The combined state immediately prior to a particle encountering a detector can be represented as:
$|\Psi\rangle(|\alpha\rangle+|\beta\rangle)=|\Psi\rangle|\alpha\rangle+|\Psi\rangle|\beta\rangle$ where $|\Psi\rangle$ is the state of the detector and $|\alpha\rangle$ & $|\beta\rangle$ are the superposed states of the particle. After the encounter the state will evolve to: $|\Psi_Y\rangle+|\Psi_N\rangle|\beta'\rangle$ with the two parts remaining orthogonal in U. This is an example of an entangled state where 'entanglement' refers to the fact that the entire state cannot be written simply as a product of a state for one of the subsystems (detector) with that of the other (particle). In addition, the $|\Psi_Y\rangle$ state is likely in itself an entangled state while the $|\Psi_N\rangle|\beta'\rangle$ state is not entangled.



A characteristic feature of entangled states is the the 'jumping' that occurs with the operation of R can have seemingly non-local action – the EPR (Einstein – Podolsky – Rosen) effect.

Quantum entanglement heeds neither spacial or temporal ordering and lies somewhere between direct communication and complete separation – and it has no classical analogue whatsoever. Einstein found th prospect of such an effect deeply disturbing, referring to it at 'spooky action at a distance'.



5.18 The magic dodecahedra explained

Appendix B: The non-colourability of the dodecahedron

Appendix C: Orthogonality between general spin states

6 Quantum theory and reality

6.1 Is R a real process? There is a fundamental difficulty with trying to find a clear scale at which the quantum level of activity actually gives way to the classical.

6.2 Many-worlds-type viewpoints. Here one accepts the state vector, evolving entirely under the action of U, is providing the true reality. According to this view, the procedure R would be an illusion, apparently arising as a consequence of how a macroscopic observer would perceive in a quantum entangled world. Unsatisfactory because the details of the illusion are not revealed nor is the reason that the squared moduli of the complex number weighting factors become relative probabilities.

6.3 Not taking $|\psi\rangle$ seriously. There are many viewpoints which consider $|\psi\rangle$ to be just a calculating device with no bearing on "reality". The most powerful reason for rejecting this argument is that the physical state $|\psi\rangle$ is uniquely determined by the fact that the outcome YES, for this state, is certain. No other physical state ha this property.

6.4 The density matrix. The pragmatic physist says that questions of reality are philosophical and irrelevent so long as the procedure works. The probability density matrix represents a probability mixture of a number of possible alternateive state vectors, rather than simply a single state vector. The idea is that one cannot operationally distinguish between the uncertainty as to which state the system is actually in and the quantum mechanical probabilities that would result from the R procedure. The density matrix is written as $|\psi\rangle\langle\psi|$ which represents a kind of 'tensor product' between the state vector and its complex conjugate. We are accepting that the physical 'reality' of any situation is to be described by some definite state vector, but there is a classical uncertainty as to what this state vector actually is. The density matrix gives the correct probability no matter how this probability is considered to be made up out of classical and quantum-mechanical components.

6.5 Density matrices for EPR pairs. The density matrix provide some flexibility and comfort in that a single matrix will deliver the correct result regardless of whether the direction that the experimenter chooses for measurement (I.e. up/down or left/right). However, the density matrix cannot explain the correlations between the measurements of two observers measuring two separate entangle parts of a single system.

6.6 A FAPP explanation of R? However, the flexibility of the density matrix to describe different measurement directions equal well also allows them to describe physically impossible situations; such as Schrödinger's cat being both dead and alive at the same time. Merely knowing the density matrix does not tell us that the system is the probability mixture of some particular set of states that give rise to this particular density matrix. There are always numerous completely different ways of getting the same density matrix, most of which would be 'absurd' from a common-sense point of view. Moreover, this kind of ambiguity holds for any density matrix whatsoever. The entire quantum state is still required and the U and R procedures continue to exist.

6.7 Does FAPP explain the squared modulus rule? The use of a density matrix implicitly assumed that a probability-weighted mixture is appropriately described by such an object and the notion of the squared modulus rule is thus inbuilt. Hence, the squared modulus rule is not explained. R is something different from U and not a consequence of U.

6.8 Is it consciousness that reduces the state vector? No! The universe mus exist and progress in the absence of a conscious entity to observe it.

6.9 Taking $|\psi\rangle$ really seriously. If one seriously accepts U and R and the implied 'jumps' then one must introduce some change to quantum theory to join it together properly. One way of doing this is to consider the wavefunction of a single, initially localised, free particle, to spread outwards in all directions into space as time progresses with a very small probability that the wavefunction will be 'reset'. This would have to occur once every 10^8 years – hardly likely to be noticed. Ingenious, but ad-hoc and without supporting evidence.

6.10 Gravitationally induced state-vector reduction? There are strong reasons for suspecting that the required modification to quantum theory will involve gravity in a serious way. However, superposition of state will necessarily involve superposition of geometries (as particles exist in different locations) and how to relate 'equivalent' positions in two geometries is profoundly obscure.

6.11 Absolute units. The idea (due originally to Max Planck (1906) and followed up by Wheeler (1975)) is to use the tree most fundamental constants of Nature, the speed of light c, Planck's constant $\hbar$, and Newtons constant of gravitation G, as units of length, mass and time so that these three constants all take the value units.

second = $1.9x10^{43}$
metre = $6.3x10^{34}$
gram = $4.7x10^{4}$
degree kelvin = $4x10^{-33}$
density of water = $1.9x10^{-94}$

6.12 The new criterion. The proposal in ENM was for a criterion, according to which two states might be judged, with regards to their respective gravitational fields, to be different to one another for them to be able to co-exist in quantum linear superposition. In this idea however, we regard widely differing states as unstable and we ask that there be a rate of state-vector reduction determined by such a distance measure. If we take a sphere with mass m and radius a the reduction time measured in absolute units is roughly:

$$\frac{1}{20\,\rho^2 a^5}$$

This gives reduction times of about

- $10^{186}/a^5$ for water
- 10^{58} (over 10 million years) for a nucleon
- 0.05 sec for a 1 micron drop of water

In general when we consider an object in a superposition of two spatially displaced states, we simply ask for the gravitational energy that it would take to effect this displacement. The reciprocal of this energy measures a kind of 'half-life' for the superposed state. The decay process is the reciprocal of a small uncertainty in mass-energy of the initial particle – an effect of Heisenbergs uncertainty principle.

7 Quantum theory and the brain

7.1 Large-scale quantum action in brain function? According to the conventional viewpoint, brain action is to understood in terms of essentially classical physics. Eccles (199) and Penrose ENM have provided alternate views.'OR', standing for objective reduction, will be used to denote the process which is needed in quantum physics to replace the R process.

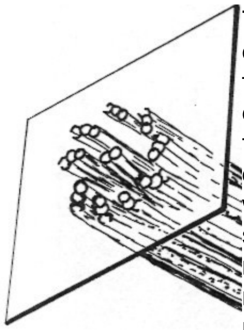
Quantum coherence refers to phenomenon when large numbers of particles can collectively cooperate in a single quantum state which remains essentially unentangled with its environment. This occurs dramatically in super conductivity and super fluidity where the characteristic ingredient is an energy gap which much be breached by the environment if it it to disturb this quantum state. Hence these phenomenon are known to occur at very low temperatures but there is some evidence for the phenomena at higher, near biological, temperatures. In 1968 Frohlich suggested a possible role for collective quantum effects in biological systems. This involved vibrational effects at 10^{11}Hz.

7.2 Neurons, synapses, and computers. What procedures govern the synaptic changes involved in brain plasticity? Hebbian modification cannot be th answer because we have ruled out purely computational action. Edelman's “Bright Air, Brilliant Fire” (1992) proposed a form of Darwinian principle with significant associations with how the immune system recognises substances, but this is again classical and computational. If it is similar to the immune system then the immune system must involve quantum effects (see Conrad 1990, 1992, 1993)

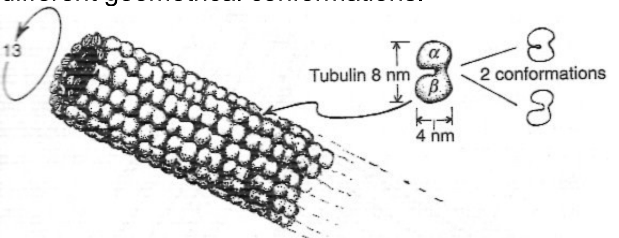
7.3 Quantum computation. Proposed by Deutsch (1985), Feynman (1985, 1986) Benioff (1982) and Albert (1983). Quantum computing is equivalent to Turing computing but much faster – particularly for a class of problems related to complexity theory. The putative OR process would still be required to have an essentially non-computable scheme.

7.4 Cytoskeletons and microtubules. The cytoskeleton provides the framework that holds a cell in shape, but it plays a much larger rle for a single cell including skeleton, legs, blood circulatory system and nervous system all rolled into one. (see Hameroff's “Ultimate Computing” (1982) and Hameroff and Watt (1982) and articles in the Journal Nanobiology)

The cytoskeleton consists protein-like molecules arranged in various types of structure: actin, microtubes, and intermediate filaments. Microtubes are hollow cylindrical tubes, 25nm OD and 14nm ID.



These are are sometimes organised into larger tube-like fibres that consist of nine doublets, triplets, r partial triplets, of microtubes, organised in an arrangement with a fan-like cross-section with sometimes a pair of microtubes running down the centre. Each microtube is itself a protein polymer consisting of sub-units refered to as tubulin, a 'dimer' consisting two subunits α-tubulin and β-tubulin (450 amino acids). It is a globular protein pair, somewhat peanut shaped and organised in a slightly skew hexagonal lattice along th entirety of the tube.. There are generally 13 columns of tubular dimmers to each microtube. Each tubulin dimmer (8nmx4nmx4nm) can exist in two different geometrical conformations.



The 'control centre' of the cytoskeleton appears to be the centrosome which includes the centriole which consists of two cylinders of nine triplets of mictotubes, where the cylinders form a separated 'T'. The centrosome is critical to mitosis. It is believed that the cell/nucleus and cytoskeleton/centrosome came together as a result of an ancient infection that resulted in the symbiotic relationship found in eukaryotic cells.

The organisation of mammalian micro-tubes tend to have a relationship with the Fibonacci numbers (0 1 1 2 3 5 8 13 21 34 55 89 144 ...). Hameroff ha argued that the microtubes may play roles as cellular automata where the relationship to the Fibonacci numbers has an information processing advantage.

Microtubes run long the lengths of the axons and dendrites and seem to be responsible for maintaining the strengths of synapses and guiding the growth of new nerve endings towards their targets. Note that brain cells do not undergo mitosis so this role of the centrosome is not required.

If micro-tubes do play a computational role then they would represent a huge increase in computational power over estimates based on neurons alone with 10^7 dimmers per neuron.

7.5 Quantum coherence within microtubules? There is some evidence for the 10^{11}Hz oscillations within cells that Frohlich predicted regarding the possibility of quantum-coherent phenomenon in biological systems. A Bose-Einstein condensate (superconductivity & superfluidity) involves features of quantum wavefunctions operating at a macroscopic scale due to the whole system of particles operating very much as the quantum state of a single particle would (possibly related to the single sense of self). The microtubes ID appears to be the right size to act as dialectric waveguides. The micotubes contains 'vicinal' water which has a geometric structure imposed by the surrounding hydrogen bonding units. There must be non-classical, quantum effects of some form at this level.

7.6 Microtubules and consciousness. General anaesthetics are a group of chemically different substances including the chemically inert gas xenon. Hamerhoff and Watt (1983) have suggested that it is the weak van der Waals interactions which interfere with the normal switching action of tubulin. Note that anaesthetics are effective on everything from Mammals to green slime mould. This lends support to the idea that anaesthetics act on the cytoskeleton. Hence we could say that the cytoskeleton is necessary (but not sufficient) for consciousness.

7.7 A model for a mind? “Our picture, then, is of some kind of global quantum state which coherently couples the activities taking place within the tubes, concerning micro tubules collectively right across large areas of the brain. There is some influence that this state (which may not be simply a 'quantum state', in the conventional sense of the standard quantum formalism) exerts on the computations taking place along the micro tubules - an influence which takes delicate and precise account of the putative, missing, non-computational OR physics that I have been strongly arguing for. The 'computational' activity of conformational changes in the tubulins controls the way that the tubes transport materials along their outsides, and ultimately influences the synapse strengths at pre- and postsynaptic endings. In this way, a little of this coherent quantum organisation within the microtubes is 'tapped off' to influence changes in the synaptic connections of the neural computer of the moment.“ pg 375.

In this way quantum counter-factuals might be utilised to effect of a neural computation if it were to be performed without it actually needing to occur.

7.8 Non-computability in quantum gravity: 1 The topological equivalence of 4-manifolds is computationally unsolvable (equivalent to the halting problem). Computational unsolvable asserts that there is no systematic (algorithmic) means of solving all the problems in the class. It does not imply that particular problems in the class do not have solutions. There may also be problems which are inaccessible to humans.

7.9 Oracle machines and physical laws. If the quantum-gravity theory did enable a physical device to be constructed to solve the halting problem then it still would not be able to solve all of the problems arising from the Goldel-Turing argument. Turing introduced the idea of a physical oracle machine that could solve the halting problem - but this can only be possible if the physical laws in nature are not computational. From this we can conclude that "Human mathematicians are not using a knowably sound oracle algorithm in order to ascertain mathematical truth." This dos not imply that humans can are as powerful as an oracle machine and solve every halting problem.

7.10 Non-computability in quantum gravity: 2 It seems reasonable to rule out space-time geometries with closed timelike lines (due to sequential circular light cone tilting) as descriptions of the classical universe, but they should not be ruled out as potential occurrences involved in a quantum superposition. The halting problem could be solved by an infinite timelike loop and the possibility of a quantum counterfactual to this effect would allow its result to be know without even performing such a calculation!

7.11 Time and conscious perceptions. Time is perceived to flow and space is not but there is nothing in the equations to require this. An orderly sequential time is difficult to pin down in the brain (Dennet) and the point that free will acts is similarly elusive. Perhaps consciousness has evolved in support of slow deliberation and is simply a passenger on the faster automated responses. But there are examples of motor-racing, squash and table-tennis which appear to involve rapid conscious thought.

Beware of logical conclusions concerning temporal ordering of events when quantum effects are involved. Conversely, contradictory conclusions of classical reasoning about temporal ordering is a strong indication that quantum effects are at work.

7.12 EPR and time: need for a new world-view. Various time related arguments make it diffuclt to see how both Einsteinian relativity and quantum realism can be retained concurrently and reconciled. However, Einsteinian relativity enhanced the Newtonian physics rather than replaced it.

A couple of crazy options with merit have been proposed, but neither are crazy enough.

8 Implications?

8.1 Intelligent artificial `devices'. Computers cannot be intelligent (understand) but it may still be possible to construct an intelligent devise (biological or mechanical). There are proposals to use quantum effects for cryptology such that a message cannot be intercepted without detection. It is not entirely necessary to find the theory prior to construction but "it would be hard to see how one could even tell when a given insentient object is behaving non-computably. The whole concept of computation is very much bound up with theory, rather than being directly an observable matter" pg 394. In addition to knowing the theory of OR we would also need to know how the phenomenon results in consciousness before we could construct an intelligent device.

8.2 Things that computers do well - or badly. The time required for a computer to examine the possible moves in a game can be estimated by $T=tp^m$, where t is the time required per alternative, p is the number of possible moves and m is the depth of moves considered. In Drafts $p\approx4$, and a computer might consider $m\approx20$. In Go $p\approx200$, so a computer is limited to $m\approx5$. Chess is intermediate. $t_{human} >> t_{computer}$ but human judgement can drastically reduce p which is much more effective. This gives some indication of why computers can play good Drafts (not Go), are better at long chess problems (not short), and have an advantage with short time limits (per decision).

Computers do not have understanding and this can result in crazy answers at times – but then, so can humans.

8.3 Aesthetics, etc. Aesthetic and moral judgements are also missing from computers – are these absolutes? What about free will?

8.4 Some dangers inherent in computer technology. Highly connected network, instability, pace of change, privacy, industrial espionage, identity fraud, computer sabotage. Understanding is missing.

8.5 The puzzling election. Beware computer geeks writing a virus to rig election results so that no-one notices!

8.6 The physical phenomenon of consciousness? Where might one expect to find consciousness in the known world? Elephants can express religious type responses to deceased relatives. Certainly apes and squirrels are conscious.

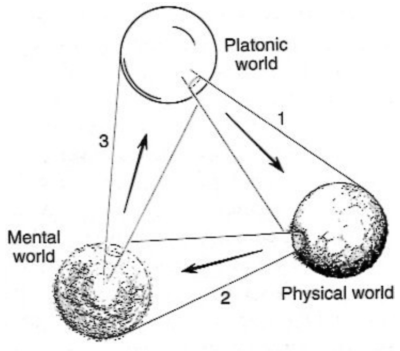
"The picture that I am proposing for micro tubules is that there are 'quantum-coherent oscillations' taking place within the tubes, and these are weakly coupled to 'computational cellular-automata-like' activity taking place in the conformational switchings of tubulin dimers on the tubes. So long as the quantum oscillations remain isolated, the level would be too low for OR t take place. However, the coupling would entail that the tubulins also gel involved in the state, and at a certain point OR would be effected. What we need is that OR comes in before the environment of the microtubules become entangled with the state, because as soon as that happens the non-computable aspects of OR are lost, and the action is just the random R-process." pg 409

The cerebellum appears to act entirely unconsciously and is a worth point of research in contrast to the conscious cerebrum.

8.7 Three worlds and three mysteries. Part I concentrated on conscious mathematical understanding in order to make the strong claim that it is impossible for mere computation to support or even simulate it. There is nothing special about mathematical understanding. Therefore understanding but be based on a physics that lies beyond computational simulation.

Part II attempts to find a scope of physical action beyond computation.

1. Why do such precise and profoundly mathematical laws play such an important role in the behaviour of the physical world?
2. How is it that perceiving beings can arise from out of the physical world?
3. How is it that mentality is able seemingly to create mathematical concepts out of some kind of mental model?



Einstein found a precise mathematical relationship in the very structure of space-time – he was not just 'noticing patterns' or searching for a physical phenomenon to fit a theory. Also the theories of Galileo and Newton were not invalidated but continue to survive in their place in the newer scheme.

The essential point of the arrows (in the previous figure) is not so much their direction but the fact that in each case they represent a correspondence in which a small region of one world encompasses the entire next world.

Godel's argument does not argue in favour of there being inaccessible mathematical truths. What it does argue for, on the other hand, is that human insight lies beyond formal argument and beyond computable procedures.

Einstein disrupted our notions of space and time then Quantum mechanics disrupted our nature of matter. The notion of cause and effect is also profoundly disturbed with a counter-factual possibility having an apparent role.

The predicted OR theory at the quantum mechanical boundary simply opens a possible opening for non-computable action but it is not the whole explanation for consciousness.

Epilogue

Bibliography

Index

Further Reading

Pg.62 footnote 10 regards AI
Pg.62 footnote 11 re Church's lambda calculus

ULTIMATE COMPUTING - Biomolecular Consciousness and NanoTechnology - Stuart R. Hameroff

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