Minds, quantum measurement, and gravity

From **Michael Berry** in the physics department, Bristol University, UK

ROGER PENROSE has provoked a great deal of discussion and controversy with his recent book *The Emperor's New Mind* (Oxford University Press 1989). (For a summary and review of the book's arguments by Frank Tipler, see *Physics World*, November 1989, p45.) Its main proposal is that three problems which are usually regarded as separate are actually part of the same problem, and so might eventually find a common solution.

The first is the problem of mind, and especially consciousness. Penrose disagrees with the prevailing scientific opinion, based on ideas of artificial intelligence, that mind is software, a property of the program, or algorithm, executed by the hardware of the brain, and that consciousness is a higher-level, emergent, property of this algorithm. Using a variety of arguments, centred on Gödel's undecidability theorem, he seeks to demonstrate that thought – even mathematical thought – contains essentially non-algorithmic aspects, and so could not be modelled with a computer. This position might appear to imply that mind is supernatural, but Penrose does not take this view, believing rather that the operation of the mind depends on still-unknown physics whose laws are non-algorithmic – that is, where some problems can be precisely posed in terms of the laws but cannot be solved by running a program based on them. An example of such a question (which has stimulated interest among mathematicians) is: does a given point lie inside the Mandelbrot set?

One area of physics where this non-algorithmic aspect might enter is, Penrose thinks, quantum measurement, which is the second of the three problems. He emphasises that in quantum mechanics there is an awkward coexistence between two kinds of time-development. On the one hand, there is the unitary evolution (U) of states according to the Schrödinger equation. On the other, there is the essentially non-unitary 'reduction of the wavepacket' (R) which projects the system into an eigenstate whenever a measurement is made. Any more general theory in which R occurs naturally, that is, without having to be separated from U by the artificial decision to dignify some interactions with the title measurements, must, he argues, be nonlinear, and might well be non-algorithmic.

This leads him into the third problem, which is the integration of gravity with the rest of fundamental physics. Without providing a theory of quantum gravity, he gives reasons why gravity might be the missing ingredient in the explanation of the quantum R-process. Being a weak force, gravity would not affect the predictions of quantum mechanics at the atomic and molecular levels where it has been so spectacularly successful. Penrose suggests a 'one-graviton criterion', related to the local spacetime curvature, to determine when gravitational nonlinearities might generate R, and claims that a preliminary estimate locates this somewhere near the level that could be relevant for the activity of neurons.

About 20 people, working in a variety of fields, gathered in Cambridge on 6–7 August to discuss the issues raised by Penrose's book at a seminar organised by Graeme Mitchison and Martin Rees and supported by the Thyssen Foundation. As is inevitable and proper with such wide-ranging and multiply connected questions, discussion tended to be fractal, but in an attempt at orderliness the contributions were chosen to emphasise biology on the first day, and physics on the second. What follows are my idiosyncratic selections and recollections.

Horace Barlow, a neurophysiologist at Cambridge, pointed out that despite our introspective impressions the main objective consequence of consciousness for the human species occurs at the social level. This happens through each brain modelling the behavioural propensities of other brains, populating itself with these mind-models, and thus influencing its own behaviour. Such social interaction lies at the highest level of a hierarchy whose lowest level is the interaction between fundamental particles. There would be many gaps to fill before revisions of basic laws, such as Penrose proposes, could increase our understanding of interactions at the highest levels.

The anatomy of the cortex suggests that distributed patterns of activity – correlations between the activities of many cells – underlie perception, as was described by Valentino Braitenberg (Tübingen), who studies brain structure under the microscope. He noted the apparent analogy between this type of selection and the R-process of quantum measurement. Distributed cellular action was also discussed by Semir Zeki (University College London), who studies the cortical visual system, and who described how perception of the constancy of colour under varying illumination depends on context rather than simply local physical illumination. There are specialised areas of the cortex devoted to colour constancy, motion, and other visual attributes. In vision these different attributes are integrated by means of a complicated system of feedback between different levels of the cortex.

Graeme Mitchison (Cambridge), who studies the psychophysics of vision, described experiments which suggest that attention, acting like a searchlight, can 'illuminate' in succession different aspects of the retinal image and thereby pick out visual attributes that belong together. Doubts were expressed about whether such studies of attention help in the understanding of consciousness, and whether metaphors useful to those working in one field might not be confusing to outsiders. Mitchison also discussed Crick and Koch's recent theory which proposes that the 40 Hz oscillations of cortical neurons may serve to bind together the components of a visual scene to give a unified conscious percept.

In his final chapter, Penrose had based some far-reaching speculations on recent experiments by B Libet. These are supposed to show that a sensory experience can seem to happen before the completion of the neural events necessary for it, and Penrose invokes them in questioning whether conventional concepts of the flow of time apply to consciousness. Ian Glynn, a membrane physiologist at Cambridge, argued that the evidence for antedating is unconvincing, and that even if it does exist it need not be mysterious. He illustrated the dangers of using a time-marker to establish precedence, when what matters is the time of starting rather than completion, with the story (Genesis 38) of the birth of Tamar's twins: when a hand appeared, the midwife bound it with a scarlet thread, to establish his rights as first-born, but then the hand was withdrawn and his brother emerged first!

Aaron Klug, a Cambridge molecular biologist, took up Penrose's theme that the assembly of perfect quasi-crystals must involve non-local interactions, possibly quantum mechanical, using as illustration the assembly of viruses. This appears to be a similar problem, involving tilings not of a plane but a sphere, in 'football' patterns of hexagons and pentagons, but no non-local interaction is necessary because misplaced atoms get detached and replaced elsewhere. There was dispute about whether this type of non-locality, achieved by a statistical mechanical mechanism, was the same as that required in a quasi-crystal.

On the second day, Roger Penrose (Oxford) began with a simplified review of the Godel–Turing demonstration of the existence of undecidable but known-to-be-true propositions. This involves Cantor's 'diagonal slash', in which propositions with a single integer argument n are labelled in sequence and then applied to the same n that labels them. He described several 'resolutions' of this undecidability 'paradox'. His opinion is that the only way to make sense of 'meaning' and 'understanding' is for the operation of the brain to depend in some essential way on non-algorithmic physics, but that it is difficult to see how (or why) a brain operating purely algorithmically, in a manner adequate enough to develop mathematics would evolve. George Kreisel, a logician at Oxford, was puzzled at the suggestion that physical laws might be non-algorithmic. Concepts such as computability apply to infinite sets, but in physics we can deal only with finite sequences, so it is difficult to see how any assertion of non-computability could ever be tested.

The remaining contributors were all physicists. David Deutsch (Oxford) emphasised that computability in the sense of Turing is an assertion involving physics – for example the assertion that the internal states of a computer (e.g. Turing's original paper tape) are definite (0s and 1s) implies that computers can be modelled by classical mechanics. He described quantum computers, whose internal states (inputs and outputs of gates) can be superpositions of 0s and 1s. For such devices (still largely imaginary), complexity theory is different; for example, there are some tasks which can be carried out exponentially faster by a quantum computer than by a Turing computer, quantum computers might be able to prove theorems much faster than they can provide the proofs (cf. Fermat's celebrated margin), or they could carry out several tasks at once, in orthogonal subspaces ('quantum parallelism'). Deutsch doubted whether consciousness really depends on the 'non-algorithmic' properties that Penrose considers essential, but suggests that quantum computers might possess those properties.

The only quantum computational device that has actually been constructed was described by Charles Bennett (IBM Yorktown Heights). This employs polarisation measurements on photons to enable two people to publicly (that is, in the presence of an eavesdropper who can intercept some of the photons) develop and verify a secret sequence of digits, which could then be employed, for example, as a key to encrypt messages passing between them.

My own contribution drew attention to what looks like a gap in quantum measurement theory. On the one hand, the distinction between a quantum system and the classical apparatus that measures it is supposed to be fundamental, but on the other we have the correspondence principle, implying that classical mechanics is contained in quantum mechanics as a limiting case. This looks like a paradox, or at least an example of complementarity (or meta-complementarity). In any case, one ought to look more carefully at the semiclassical limit, that is at the asymptotics $\hbar \to 0$. The problem is that this limit is highly singular and still not properly understood, certainly as far as it affects mesurement. Until this question about the existing quantum theory is clarified, it is premature to insist that some modification is necessary. The only relevant study I know is the analysis by N D Mermin 1980 *Phys. Rev.* D **22** 356) of a generalised Bell inequality involving spin s (rather than spin 1/2) particles, where the quantum violations occur in a range of measurer orientations that shrinks to zero in the (classical) limit $s \to 0$.

Anthony Leggett (Illinois), like Penrose, thinks quantum theory is incomplete, because linear superposition – i.e. interference – must fail at some stage if the R-process is to occur. He assessed the evidence for superposition; it persists to length scales of at least 10 m (photons) and 20 cm (neutrons), and holds for composite entities such as atoms and molecules. He suggested that superposition might fail for systems which are sufficiently complicated. A criterion for complexity could be that the 'disconnectivity' D, defined as the lowest order of correlation function required to distinguish a superposition from a mixture, is large. In seeking superpositions with large D, he proposes to employ macroscopic collective coordinates, representing for example Josephson currents.

John Bell (CERN) also thinks that quantum mechanics must be altered (see *Physics World*, August p33), and, like Penrose, inclines to the view that gravity is involved. He described a nonlinear modification, due to Diosi's development (1989 *Phys. Rev.* A **40** 1165) of work by Ghirardi, Rimini and Weber (1986 *Phys. Rev.* D **34** 470), in which a background Brownian motion, whose strength is proportional to the gravitational constant, drives sufficiently large systems into eigenstates of position. Difficulties remain, however, with energy conservation and Lorentz invariance.

At the meeting, there was no 'summing up', in which the many strands of the discussion were woven into a coherent fabric, and I shall not attempt such untangling either. But the liveliness of the contributions, and the fact that all of them were directly relevant to Penrose's themes, indicates that the controversies stirred up by his proposed synthesis are likely to remain unresolved for a long time. □

Single-mode dreams brought to life

From **Pierre Meystre** in the Optical Sciences Center, University of Arizona, USA

A SERIES of experiments conducted by a group at the Max Planck Institute for Quantum Optics, Munich, Germany, has culminated in the observation of sub-Poissonian light in a micromaser. These results, reported by G Rempe, F Schmidt-Kaler and H Walther, provide considerable new insight into the fundamental operation of lasers and masers, and elucidate the conditions necessary to generate non-classical radiation (1990 *Phys. Rev. Lett.* **64** 2783).

General wisdom has it that conventional single-mode lasers and masers operating far above threshold generate coherent radiation, just like a harmonic oscillator driven by a classical force. Such coherent radiation has a number of unique statistical characteristics that distinguish it from the so-called thermal light emitted by a spectral lamp. Although the Young interference pattern produced by coherent light is indistinguishable from that of a narrow-band thermal source, higher-order interferences, such as those produced for instance in Hanbury-Brown and Twiss experiments, lead to vastly different results.

In such experiments, the beam of light to be analysed is split into two beams which impinge on two detectors. The signals at the two detectors are then multiplied and averaged in a correlator. Varying the relative distance between the two detectors and the source results in a measurement of the correlation function between the intensity I at a time t and a subsequent time $t + \tau$. For coherent light, this experiment leads to a constant result, independent of the delay τ. In contrast, for narrowband thermal light, this correlation is a decreasing function of τ, as shown in figure 1. Thermal light is said to be bunched, that is, photons have a tendency to be emitted in bursts, in contrast to coherent light, where the probability of detecting a second photon after a first one has been measured is independent of the interval between measurements. This remarkable property is also apparent in the corresponding photon statistics, which are Poissonian for coherent light and follow a Boltzmann distribution law for thermal light. These photon statistics indicate that laser intensity fluctuations are given by the square root of the mean intensity, while for thermal light they are equal to the mean intensity (and hence are quite a bit larger).

These results were well established in the 1960s, and have a firm foundation in the quantum theory of the laser and in quantum coherence theory. It was not until two decades later, however, that the *origin* of coherence in laser light was properly understood. Motivated in part by the search for non-classical light sources, such as squeezed light for example, several theoretical studies investigated why lasers emit coherent light.

Surprisingly, and perhaps paradoxically, it was found that it is noise and dissipation that are responsible for this property. A hint