IS THE MIND MORE THAN AN ANALYTICAL ENGINE?

The Emperor's New Mind: Concerning Computers, Minds, and the Laws of Physics

Roger Penrose
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Johann Nepomuk Mälzel, appointed mechanician at the court of Vienna in 1808, was an inventor of musical instruments and a quarrelsome collaborator of Beethoven's. He was also the promoter and exhibitor of a chess-playing machine. However, the machine was a fake: A man was concealed in the instrument. Is the mind a purely mechanical device, or is there a little man hidden in it? Roger Penrose, in *The Emperor's New Mind*, tells us that the mind is more than a computer. The hidden entity, according to the author, is not a little man, but consists of Gödel's theorem and "CQG." CQG is Penrose's abbreviation for "correct quantum gravity," the ultimate—but not yet attained—quantum theory of gravitation. To Penrose, the mind, with its capability for awareness and consciousness, is more than an "analytical engine." (I invoke Charles Babbage's title for his 1833 computer invention, an information handling system based on well-understood dynamical laws.)

I do not agree with Penrose's thesis. Nevertheless, Penrose has given us a superb book. It is provocative and absorbing. It will lead you through a fascinating tour of Turing machines, Gödel's theorem, quantum gravity, quantum measurement, irreversibility and many other topics, even though the eventual application of these subjects to the author's central theme is almost incidental.

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This book spent many weeks on the *New York Times* best seller list. What is the intended audience? If you enjoy PHYSICS TODAY you will be interested. The book makes broader claims, however. Martin Gardner, in a foreword, tells us that it is for the informed layman. Indeed, Penrose tries hard to presume next to nothing about the reader's knowledge. He describes, for example, what a complex number is. But the reader who does not know even that is likely to get dragged up along a dizzyingly steep climb to Fourier transforms, Dirac notation, Hilbert space, projection operators and so on. It would require a remarkable intellect to follow all that. You need not read the book in its entirety; you can dip here and there and skim some hard parts. On the other hand, those who approach the book with too little science background will not understand enough to satisfy, and certainly not enough to evaluate Penrose's claim. But the book's presumption that it is intended for a really broad audience is our good fortune: It is priced accordingly and costs far less than the Proceedings of the 11th International Symposium on Relativistic Exciton Spectroscopy that you bought just to see what your colleagues had to say about your papers, and spent only 20 minutes with. You will give Penrose far more attention.

I have listed the book's attraction briefly. Let me now dwell on the critique in more detail. Penrose is Rouse Ball Professor of Mathematics at Oxford. His title reflects, in part, the history of classification and organization in some English universities, but there is more to it than that. To Penrose, mathematical objects, such as the Mandelbrot set, which he discusses in detail, have an absolute reality independent of their human discovery. Furthermore, he tells us that "algorithms can exist as marks on a piece of paper, or directions of magnetization in a block of iron, or charge displacements in a computer memory. But such arrangements of materials do not in themselves actually constitute an algorithm."

I disagree with the last sentence. For simplicity, I will use the number π rather than the Mandelbrot set for this discussion. In my view, information inevitably has a physical form, and it is therefore restricted both by the laws of physics and by the parts of the universe that we can use for its representation. It will not be hard to nail down enough degrees of freedom to represent the rules for calculating π. But those rules will not permit us to distinguish between π and a terribly close neighbor unless we can execute the calculation to a great many places. Such a task demands a large memory. The universe is unlikely to be so cooperative as to permit us to collect and organize enough degrees of freedom for an unlimited memory. The usual mathematical techniques, which invoke an unlimited sequence of error-free operations, are therefore unlikely to be available for real implementation. They are irrelevant—at least in their full and serious detail—for physics.

In the 1930s a body of work arose in mathematics and logic that was concerned with the limitations, quite unexpected at that time, of an unlimited sequence of information-handling steps. This body of work included Gödel's theorem and the proof of the undecidability of the halting problem of a Turing machine. Gödel's theorem is often summarized by stating that formal logical systems can give rise to "true" theorems whose proof cannot, however, be found within the system. Penrose draws a connection between this possibility of perceiving some truths outside of the capabilities of an analytical engine operating on a set of axioms and the possibly unique characteristics of the mind. I believe that Penrose's interpretation is based on an ambiguity in the use of the word "true."

But we do not really need to tangle

with such technicalities. The mind, whether by itself or augmented with an unlimited supply of paper and pencils, is a finite machine. It is therefore unrelated to Gödel's theorem. Indeed, I would assert that Gödel's theorem is unrelated to physics altogether, because the unlimited memory needed for the execution of the algorithms that constitute our typical laws of physics is unlikely to be available. Versions of Gödel's theorem valid for finite systems, based perhaps on an information-theoretic approach to that subject developed by Gregory Chaitin, are not out of the question. But such theorems do not exist yet. Those of my physics colleagues who have invested the necessary intellectual capital required to understand Gödel's theorem are likely to be unwilling to write off that investment, and they are unlikely to agree with me.

The book has a good deal to say about quantum measurement, and we meet all the usual exhibits, including Schrödinger's cat and the Einstein–Podolsky–Rosen paradox. Quantum theory of measurement is a remarkable subject. It provides room for endless debates between clever people. But when I look over the shoulders of my experimental colleagues, I note that they have no problem going about their business without the least attention to the sophisticated debates. Penrose emphasizes the distinction between two quantum mechanical processes, labeled respectively U and R. The process U is the normal evolution (in time) of the quantum state as described by the Schrödinger equation or whatever your favorite version of quantum mechanics is. The process R denotes the reduction, or collapse of the wavefunction that is supposedly associated with the measurement process. When I ask my experimental colleagues which part of their apparatus involves a departure from U, I get a blank look. There is no evidence that the universe has processes other than those described by U. Where is the minute shift in a spectral line or of a Josephson frequency that might represent the physical reality of R?

Penrose's description of the view I have just advocated, combined with its customary label, "the many-world interpretation," makes this view appear counterintuitive. I suggest, by contrast, that the problem lies with the description, its interpretation or with our intuition. Penrose implies that the mind does lots of measuring, that this in turn involves R processes and that the latter relate to CQG. One of the common problems with sophisticated discussions of measurement theory is that the discussions do not define measurement; they don't tell you how to distinguish measurement from a horseradish. Whatever "measurement" means, it is not clear that a lot of it goes on in the mind.

In a different context, Penrose refers to quantum mechanical systems described in the literature that can carry out computations. The internal dynamics of these computers are based totally on U processes. Coupling two systems temporarily to transfer information from one to the other is an innocuous process that requires no dissipation and no wavefunction reduction. Recent discussions of Maxwell's demon by Charles Bennett and others, have made that very clear. The brain undoubtedly uses heavily damped processes; the interesting degrees of freedom are strongly coupled to unimportant lattice vibrations. If you wish, you can say that this thermal environment is continually making unintended measurements. But the coupling of the vibrations to the serious variables can be described within the framework of U processes, as is done, for example, in analyses of macroscopic quantum tunneling.

The well-understood laws of physics are conservative and reversible, although the real world is filled with manifest friction, irreversibility and entropy increases. Penrose points out that the universe started out in an exceptionally low-entropy state. He then connects this with the availability of fossil fuels needed to run our cars. But when he also uses the low entropy of the initial state as an *explanation* for the second law, he has lost me. I cannot accept that the friction in my car, which makes necessary the use of fossil fuels, is a result of the universe's early low-entropy state. If the initial entropy had been much higher, the universe might be very different, but entropy would still have increased.

In a very limited sense, of course, Penrose is right in his central message. The mind is *not* a computer, if a computer is defined as an assembly of elementary digital logic functions carried out in succession. Computers are designed to act reproducibly. The mind was designed by evolution, to get us out of the way of the tiger. Reproducibility is not an asset in that. As a result we recognize Smith one day, and later realize it was Jones. But the fact that the mind differs from a computer does not mean that its function, in some deep way, requires more than biochemistry and neurophysiology. Evolution gave us several sophisticated information-handling systems, including the genetic code and the immune system. Ordinary biochemistry is all that is needed for those two systems. Why should evolution have reached much further for the mind?

Penrose correctly argues that the discrete nature of the digital computer requires something to prevent degradation of accuracy—that is, to keep a 0 from drifting into a 1. He then argues that quantum mechanics, with its discrete states, is needed for that. He is not totally wrong; after all, we are in a quantum mechanical world and all of our technical machinery is quantum mechanical if examined in a sufficiently microscopic way. But computers do not need quantized spins. Starting with Charles Babbage and continuing through Konrad Zuse's construction in the 1930s of a computer built of punched pieces of sheet metal and interlocking rods, we have seen many computers that are no more intimately connected to quantum mechanics than is a rowboat or a screwdriver. Computers built out of relays, computers based on control of fluid flow, and many other examples can be added to the list. Indeed, a computer that acted in a totally coherent quantum mechanical way would be pathological. If its Hamiltonian had even a slight "manufacturing" error—if, for example, it deviated from the exact desired Hamiltonian—we would increase the admixture of erroneous states at every step in the computation. Such a computer could perform a very limited number of steps before its information content became useless.

I believe Penrose's only serious argument for why the mind is more than an analytic engine boils down to our self-perception, our sense of awareness and consciousness. But to invoke such an argument does not require subtle physics. Penrose is not likely to analyze that ancient argument definitively. (For that matter, neither am I.)

I have devoted most of this review to a critique of Penrose's main thesis. You may find yourself more in agreement than I did—or less. But you will not find *The Emperor's New Mind* a dull book.

Crystals in Gels and Liesegang Rings

Heinz K. Henisch
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In 1970 Heinz K. Henisch of Pennsylvania State University published a slim volume entitled *Crystal Growth in Gels* (Pennsylvania State U. P.). I have treasured this volume, as no doubt have many others, because it is a useful summary of a field that is not too well known and it is written in an entertaining style. Studying it is an enjoyment—a rarity among technical books.

Eighteen years later, we now have the second modern book on the subject, *Crystals in Gels and Liesegang Rings*. This book is essentially a new treatment by Henisch, expanded from 111 to 197 pages, and is just as pleasant to read as its predecessor. Is it then worth purchasing this new volume? Given any interest at all in crystals or materials science, I believe the answer is a definite yes, whether one already owns the first book or not.

This volume, written by a recognized authority in the field, provides a thorough background on the practice as well as the theory of the growth of crystals in a gelatinous medium, be it