Roger Penrose's tryst with gravity and quantum mechanics

By Kaushik Sengupta

Imagine an eight-year-old boy sitting alone in his classroom, struggling with his test, when all his mates are out there in the playground and enjoying! The poor boy is allowed to take "timeless" tests by his kind and insightful teacher because he is "unbelievably" slow, particularly in mental arithmetic. Left to do it this way, the boy does very well, even manages to score high marks [1]. That little boy, who was once demoted to a lower class, would eventually become Sir Roger Penrose, a mathematician and theoretical physicist and one of the most outstanding and profound thinkers of our time.

Sir Roger was born in England and received his Ph.D. in 1957 from Cambridge University. He became a professor of applied mathematics at Birkbeck College in 1966 and a Rouse Ball Professor of Mathematics at Oxford University in 1973, which turned into Professor Emeritus in 1998.

Roger Penrose's fame has much to do with black holes, a supermassive compact object with a gravitational force so large that nothing, not even light, can escape from it. In 1964, Penrose invented the critical mathematical tools to describe black holes. He showed that according to Einstein's general relativity, the formation of black holes must be seen as a natural process in the time progression of the Universe's evolution. A few years later, with the late Stephen Hawking, with whom he shared a common heritage in physics asserting that at the centers of black holes, at their farthest depths, lurk a "space-time singularity" (the bizarre region of spacetime of zero volume and infinite density) where all known laws of nature cease to exist.[1] Penrose used the same mathematical tools to prove a theorem of Einstein's general relativity (the celebrated Penrose-Hawking Singularity Theorem) asserting that at the centers of black holes, at their farthest depths, lurk a "space-time singularity" (the bizarre region of spacetime of zero volume and infinite density) where all known laws of nature cease to exist. The Big Bang cosmological model, which is our current best model for how the entire Universe came into existence, was the result of this work. Penrose also proposed the hypothesis of "cosmic censorship," which claims that such singularities must possess an event horizon. In 1969 Penrose described a process for the extraction of energy from a black hole, as well as how rotational energy of the black hole is transferred into a particle outside the hole.

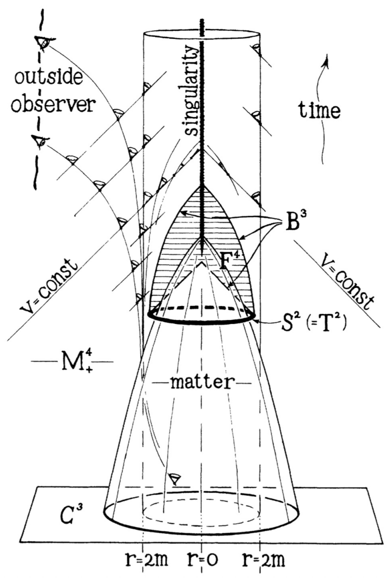


Figure 1: Figure reprinted from Roger Penrose's brief paper, "Gravitational Collapse and Space-Time Singularities" that summarizes his ingenious mathematical proof that would earn him the 2020 Nobel Prize in Physics [2]. This figure is an example of Penrose's way of rendering complex mathematics in imagery. He condensed his mathematical calculation into a single paragraph and then distilled the proof into a single image [3]. His conclusion: black holes are an inevitable consequence of unhindered gravitational collapse.

In 2019, the Event Horizon Telescope gave humanity its first look at an actual resolved image of an event horizon's shadow, a massive black hole in the galaxy M87, 55 million light years away from us. Penrose's outstanding seminal contributions to the theory of general relativity fetched him the 2020 Nobel Prize in physics. Half of the prize money was awarded to him "for discovering that black hole formation is a robust prediction of the general theory of relativity." The other half went to Reinhard Genzel and Andrea Ghez "for the discovery of a supermassive compact object at the center of our galaxy." Penrose is also exceptionally gifted as a popularizer of science having written several best-selling books.

Roger Penrose grew up in a family of exceptionally gifted individuals.[2] His mother, Margaret Leathes, was a medical specialist.[3] His father, Lionel Sharples Penrose, was trained as a medical geneticist, becoming the Director of Psychiatric Research at Ontario Hospital in London, Ontario.[4]

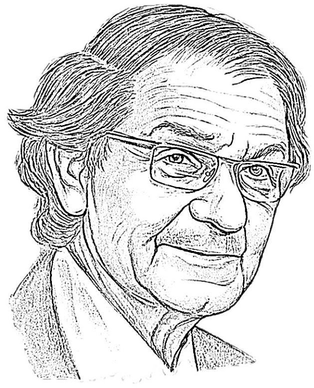
[1]Penrose served on Hawking's Ph.D. thesis committee at Cambridge. The 1988 Wolf Prize in Physics was awarded jointly to Roger Penrose and Stephen W. Hawking.

[2]Interview of Roger Penrose by Alan Lightman on 1989 January 24, Niels Bohr Library & Archives, American Institute of Physics, College Park, MD USA, https://www.aip.org/history-programs/niels-bohr-library/oral-histories/34322

[3]About his mother, Penrose said "My father really didn't let her practice medicine, though. He found it too threatening, I think."

[4]An interesting anecdote about Lionel Penrose deserves special mention. Lionel held the Galton chair in UCL from 1945 to 1965. Unfortunately, the name Galton is associated with a dark chapter in human history called "the eugenics movement" and the term eugenics was coined by the British scholar Sir Francis Galton in 1883 in his book *Inquiries into Human Faculty and Its Development*. Eugenics is the practice or advocacy of improving the human species by selectively mating people with specific desirable hereditary traits. Lionel Penrose, who earned distinction for his research in the genetics and biological foundations of mental health, believed that eugenic practices were scientifically misconceived and morally wrong. He abhorred the contemporary suggestions for eugenic practices such as the sterilization of individuals who had "mental deficiency," often explaining how this might even be nonsensical using genetic theory. He espoused the rights of children of special needs and maintained that a society could be judged by the way it looked after such

The senior Penrose was also very interested in mathematics, particularly in geometry, an interest that young Roger inherited as a child. Later in life Roger realized that he was much more “geometrically minded” than his mathematical colleagues. This mental attribute allowed him to understand and conceptualize mathematical objects of theoretical physics, significantly impacting how he tackled new research topics in his scientific career. Roger’s older brother, Oliver Penrose, became professor of mathematics first at the Open University, then at Heriot-Watt University in Edinburgh, Scotland. Oliver, who was a very precocious student, would often explain mathematics to his younger brother. Jonathan, the youngest of the three, went on to become a lecturer in psychology. From an early age, he displayed unusual talent in chess, becoming the British Chess Champion ten times between 1958 and 1969. Many think Jonathan Penrose was the most naturally gifted British chess player ever. The youngest of all, Shirley, is a professor of cancer genetics at St. George’s University of London, now emeritus.



As a young man growing up in the 1950s, Roger Penrose was greatly influenced by Fred Hoyle’s[5] radio talks, which he thought were fascinating. Unlike Oliver, Roger was not an avid reader. He preferred building models—models of objects such as polyhedral, and so on. It was his natural ability of visualizing complex objects or ideas that allowed him to successfully critique a model of the Universe promulgated by Fred Hoyle. Hoyle, in one of his radio talks had given the impression that, when the speed of a galaxy reached the speed of light, it would suddenly disappear from view in his steady state model. This picture bothered young Penrose as we shall shortly see.

Penrose met Dennis Sciama[6] in a restaurant when he was an undergraduate at Cambridge. Sciama was introduced to him by Oliver as a cosmologist (Oliver and Dennis were friends and fellow research students at Cambridge). The first encounter cast a lasting impression on Sciama as Roger complained to him about his uneasiness with Hoyle’s picture of the Universe:

> Surely, you can always see the galaxy. You draw back your light cones, and any galaxy crosses the cone. Apparently he [Sciama] hadn’t thought about this before and was very impressed. . . I don’t think they [Hoyle and Sciama] were used to drawing pictures; whereas, that was the sort of thing I did naturally, being geometrically minded.

It turns out Penrose was right after all. The experience brought him much delight and lifted his self confidence. More importantly, Dennis Sciama became his early mentor. Shortly after, Penrose joined as a research student at Cambridge in pure mathematics. Although their research fields did not intersect, the two continued with their regular discussions on physics, cosmology, and other topics. Penrose benefitted immensely, learning not just cosmology, but physics in general. Sciama became a tremendous influence as he instilled in Penrose his enthusiasm in cosmology, the subject that was very important to Penrose.

Lectures on quantum theory by Paul Dirac and on general relativity by Hermann Bondi influenced him even further. In 1958 he obtained his Ph.D. under the supervision of geometer John Todd. His thesis was on tensor methods in algebraic geometry.[7]

So far we have touched upon Penrose’s stellar contributions in general relativity and black hole information. But only few people (relatively speaking) know about his work in quantum mechanics, particularly concerning the quantum measurement paradox. To understand the significance of Penrose’s involvement in quantum mechanics, we need to briefly talk about the relation between two great discoveries of the twentieth century—general gravity and quantum theory. However, the two theories, though exceedingly successful in their own rights, are not infallible, both with their own limitations. Before getting into Penrose’s way of thinking about each, it is helpful to explore the deficiency of each theory first.

Largely due to Penrose’s work with Stephen Hawking, we now know that general relativity predicts that the Universe began in the big bang. So Einstein’s theory does imply that time has a beginning although Einstein himself was never happy about the idea. The two physicists further showed that general relativity predicted that time would come to an end inside a black hole. Hence, the equations of general relativity break down both at the beginning and the end of time. This implies that the theory cannot predict what would emerge from the big bang. It was subsequently realized that because general relativity is incompatible with quantum theory, it breaks down at the big bang.

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individuals. According to his daughter, Professor Shirley Hodgson, Lionel Penrose was able to instill his conviction into practices of his department which still bears Galton’s name but has since shed any connotations of racism or racial superiority.

[5] The British mathematician and astronomer, Fred Hoyle, is best known as the proponent of the steady-state theory of the Universe. His work on stellar nucleosynthesis performed with William Fowler and Geoffrey and Margaret Burbidge, resulted in a 1957 paper that is regarded as a milestone in modern astrophysics. But Hoyle’s stubborn refusal to accept the Big Bang theory—and his adherence to fringe ideas in other fields—made him an outlaw in the field he had helped to create. Ironically, it was Hoyle who coined the term “Big Bang” in 1950 while he was doing his series of radio lectures on astronomy. He later claimed that he did not intend to disparage the theory through this nomenclature, as many have suggested, but merely to describe it.

[6] Dennis Sciama was the British physicist who, through his own work and that of his students, played a major role in developing British physics after the Second World War. He was Stephen Hawking’s thesis advisor. Sciama was a passionate believer in the Bondi–Gold–Hoyle steady-state theory in which the Universe always expands at a constant rate.

[7] Before this, Penrose was placed under the supervision of mathematician W. V. D. Hodge. But this association was short-lived. After one year, he was “thrown out” of the class for not being able to find a solution to the problem assigned to him. “He [Hodge] was very polite all the time, and I tried to explain to him that the problem he suggested had no solution. He was always terribly polite, although he didn’t believe me. He never quite said so in so many words. . . "

Much work has already been done on what is commonly known as quantization of general relativity. The two leading contenders are string theory and loop quantum gravity. While each enjoys many attractive features, neither offers a compelling argument for a correct quantum theory of gravity. Nor there is much observational evidence to guide decisive experiments.[8] After nearly half a century of hard work, none of these efforts have given birth to an unanimously accepted quantum theory of gravity.

We now turn to the fundamental problem of quantum mechanics, referred to as the "quantum measurement problem" or the "measurement paradox." When a quantum system is measured, it becomes entangled with a measuring apparatus, which is the more extended part of the physical Universe. This measuring apparatus along with the observing physicist and their common environment should all—according to conventional understanding—have some quantum description. Accordingly, there should be a quantum description of this entire quantum state, involving not only the original system under consideration but also the apparatus, physicist, and remaining environment—and this entire state would be expected to evolve continuously, solely according to the Schrödinger equation, here denoted by the symbol **U**. However, upon measurement, the continuous evolution of the quantum system is unceremoniously interrupted and replaced by the (seemingly) discontinuous process of wave function collapse (also known as the state vector reduction or wave packet reduction, denoted by **[WP]R**). This is the famous "measurement problem." Much of current research in quantum mechanics is about comprehending how, upon measurement of a quantum system, this (seemingly) discontinuous **[WP]R**-process can come about.

Penrose believes that general relativity which predicts the existence of space-time *singularities* and quantum theory, which is vexed by the *measurement problem*, must be incomplete theories on their own. Could one be used to sort out the other? Penrose has speculated that gravity plays a role in state-vector reduction.[9] Accordingly, he proposed a model of "gravitization of quantum mechanics" in contrast to the more usual "quantization of gravity." In Penrose's words:

> This reversal of wording is deliberate, of course, indicating my concern with the bringing of quantum theory more in line with the principles of Einstein's general relativity, rather than attempting to make Einstein's theory—or any more amenable theory of gravity—into line with those of quantum mechanics (or quantum field theory).

He asked the question: do we really need to quantize gravity? Could we not imagine a dynamical classical curved space-time (in the sense of relativistic but not quantized) with some quantum matter in it? His semiclassical theory of gravity[10] conjures up the idea that a quantum state remains in superposition until the difference of space-time curvature attains a significant level. He also indicated how quantum matter, described by state vectors in a Hilbert space, could source the curvature of a classical space-time.

Of course, Penrose's ideas are not free from controversies, and they have so far not provided any clear indication of the mathematical nature of the theory that would be required for a gravitationally induced spontaneous state-vector reduction. Penrose is under no illusion. He accepts that such a mathematical framework would have to be formulated by some other means [6].[11] A fully satisfactory theory would require a revolution in the description of quantum phenomena that is similar in magnitude to the one Einstein proposed (in the description of gravitational phenomena) with his general theory of relativity. Nevertheless, Penrose's ideas have opened up new avenues of research whose threads may one day lead to the novel insights necessary for cracking the notorious quantum measurement problem.

References

[1] Roger Penrose. "New Physics for the Orch-OR Consciousness Proposal". *Consciousness and Quantum Mechanics*. Oxford University Press, 2022. eprint: `https://academic.oup.com/book/0/chapter/376470269/chapter-pdf/49114883/oso-9780197501665-chapter-14.pdf`.

[2] Roger Penrose. Gravitational Collapse and Space-Time Singularities. *Phys. Rev. Lett.* 14, 57–59 (3 1965).

[3] Janna Levin. *The Drawing That Earned Sir Roger Penrose a Nobel Prize*. Available at `https://pioneerworks.org/broadcast/picture-this-roger-penrose` (2021/10/06).

[4] Freeman Dyson. Is a graviton detectable? *International Journal of Modern Physics A* 28, 1330041 (2013). eprint: `https://doi.org/10.1142/S0217751X1330041X`.

[5] Tony Rothman and Stephen Boughn. Can Gravitons be Detected? *Foundations of Physics* 36, 1801–1825 (2006).

[6] Roger Penrose. On Gravity's role in Quantum State Reduction. *General Relativity and Gravitation* 28, 581–600 (1996).

[7] Ted Jacobson. Thermodynamics of Spacetime: The Einstein Equation of State. *Phys. Rev. Lett.* 75, 1260–1263 (7 1995).

[8] Andrei D Sakharov. Vacuum quantum fluctuations in curved space and the theory of gravitation. *Soviet Physics Uspekhi* 34, 394–394 (1991).

[8] Current proposals for quantum gravity lead to seemingly untestable predictions [4, 5]. On this ground, some have even argued that quantizing gravity is not needed after all [6] or that gravity may not even be a fundamental force [7, 8].

[9] Lajos Diósi has proposed similar ideas.

[10] The goal of semiclassical gravity is similar to that of string theory and loop quantum gravity, i.e., to attempt to unify quantum mechanics and general relativity.

[11] Penrose believes that "…present-day quantum mechanics is a limiting case of some more unified scheme, whereby the **U** and [**WP**]**R** procedures are *both* to be approximations to some new theory of physical reality."