

Nobel Prize in Physics 2020
Roger Penrose

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Georgia Institute of Technology

11 November 2020

Understanding the 2020 Nobel Prize in Physics

From the pioneering theoretical work on black holes, to observing the galactic center of our Milky Way.



Predrag Cvitanović
(and Roger Penrose)
School of Physics, Georgia Tech



Erin Wells Bonning
Director of Planetarium, Emory University

Join us virtually, as experts from Georgia Tech and Emory University explain the 2020 Nobel Prize in physics. After the presentation, the speakers will answer questions from the audience so come curious!

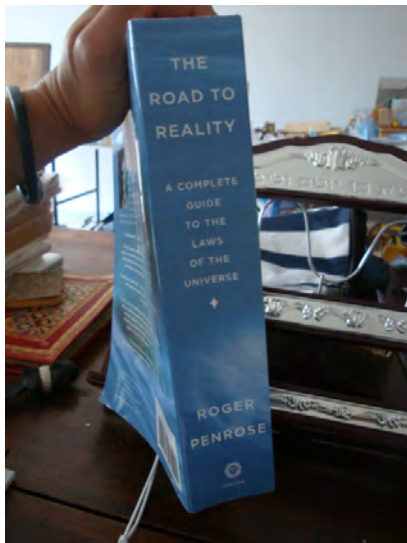
Wednesday Nov 11th
7pm EST

the morning of the Nobel Prize : wow, Penrose !!!



"The Road to Reality" should always be by your side

The Road to Reality



weighs in¹ at 3 lb and **1,099** pages :)

¹R. Penrose, "Applications of negative dimensional tensors", in *Combinatorial mathematics and its applications*, edited by D. J.A. Welsh (Academic, New York, 1971), pp. 221–244.

this evening : the world through Roger Penrose's eyes

There is only one thing which interests me vitally now, and that is the recording of all that which is omitted in books. Nobody, as far as I can see, is making use of those elements in the air which give direction and motivation to our lives.

— Henry Miller, *Tropic of Cancer*

- Asked on Oct 9, 2020, upon receiving Nobel prize:
What is your advice to young people?
- Penrose: advice to young people? Giving it is not a good idea. But do what you find exciting, do what you find beautiful.

age 10 - a boy flummoxed by problems of mathematics

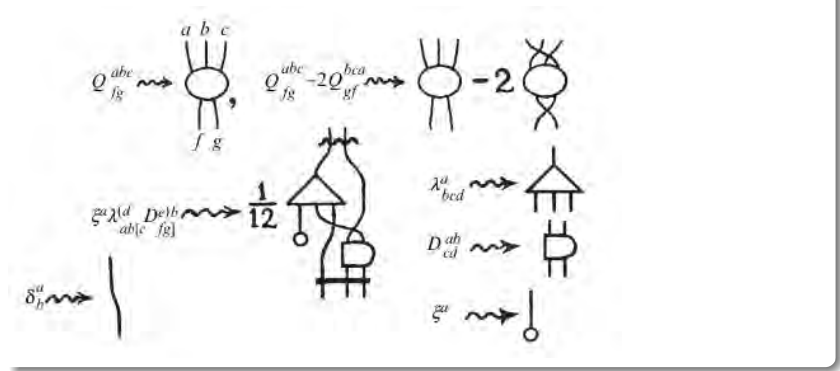
Teachers: His problem-solving skills too leisurely for school

Penrose: 'I was moved down a class'

age 21 - math for those who don't 'get' equations

invents

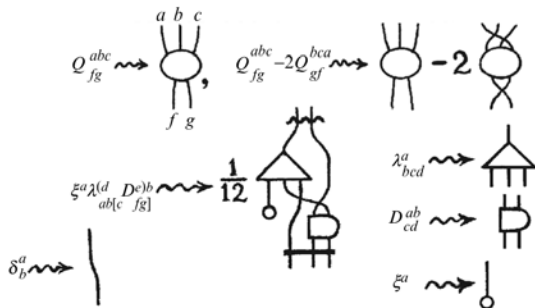
diagrammatic calculations



first shows it in a publication 17 years later²

²R. Penrose, "Applications of negative dimensional tensors", in *Combinatorial mathematics and its applications*, edited by D. J.A. Welsh (Academic, New York, 1971), pp. 221–244.

calculations for those who “see” math



$$\text{---} = \text{---} - \text{X}, \quad \text{---} = \text{---} + \text{X} + \text{X} - \text{X} - \text{X} - \text{X}$$

$$\text{---} = \text{---} + \text{X}, \quad \text{---} = \text{---} + \text{X} + \text{X} + \text{X} + \text{X} + \text{X}$$

$$\text{---} = \text{---} - \text{X}, \quad \text{---} = \text{---} + \text{X} + \text{X} - \text{X} - \text{X} - \text{X}$$

$$\xi^{[a\eta^b]} \rightsquigarrow \frac{1}{2} \text{---}, \quad \xi^{[a\eta^b\zeta^c]} \rightsquigarrow \frac{1}{6} \text{---}, \quad \xi^a \rightsquigarrow \text{---}, \quad \eta^a \rightsquigarrow \text{---}, \quad \zeta^a \rightsquigarrow \text{---}$$

age 23 in Amsterdam for a math conference

sees Escher's work, so



Penrose son and father construct the impossible tribar

Escher draws it



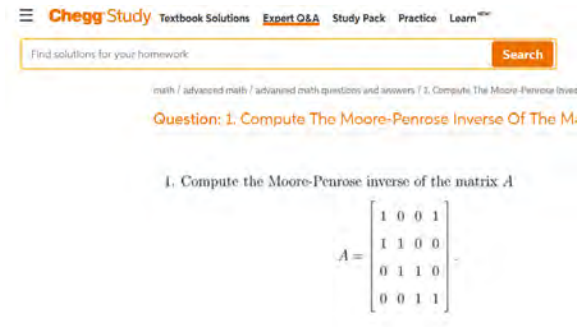
impossible waterfall

age 24 : 'division by 0' for matrices

(re)invents Moore-Penrose inverse of a matrix³

that “has no inverse”

our undergrads pay cool \$\$ for it :



The screenshot shows the Chegg Study website interface. At the top, there is a navigation bar with the Chegg logo and links for Textbook Solutions, Expert Q&A, Study Pack, Practice, and Learn. Below the navigation bar is a search bar with the placeholder text "Find solutions for your homework" and a "Search" button. The main content area displays a breadcrumb trail: "math / advanced math / advanced math questions and answers / 1. Compute The Moore-Penrose Invert". Below this, the question is stated: "Question: 1. Compute The Moore-Penrose Inverse Of The M". The matrix A is defined as:

$$A = \begin{bmatrix} 1 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix}$$

today we use it all the time (neuroscience, big data, . . .)

³R. Penrose, Math. Proc. Cambridge Philos. Soc. 51, 406–413 (1955).

age 27 : a math PhD who knows no physics

Penrose:

“I had decided I was going to start learning some physics, in a serious way. I had had to learn it myself because I'd never taken a proper physics course.”

age 27 : PhD & a fateful encounter

pure maths PhD
on tensors

meets 29-old
[David Ritz Finkelstein](#)



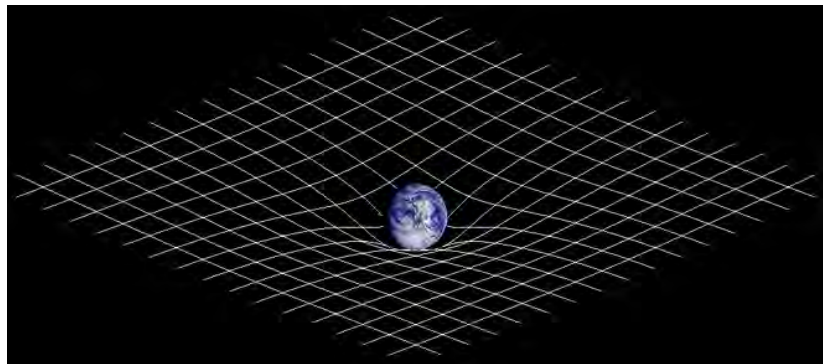
a fateful meeting that changes both men's lives forever

hear Penrose tell it

general relativity

Penrose: "... not difficult to comprehend, compared to quantum mechanics. Equations make complete sense - they are geometry"

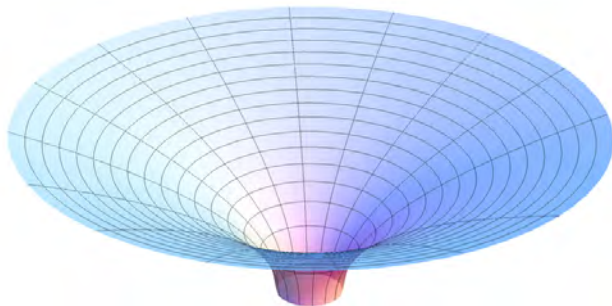
mass = spacetime curvature



too much mass \Rightarrow fall into a hole ?

Finkelstein London seminar

extending Schwarzschild's metric



beyond the black hole horizon —a basic ingredient of the current understanding of black holes — was a revelation to Penrose.

figure Wikipedia / Flamm

the switch

after the seminar Penrose explains to Finkelstein his spin-networks, and the two men exchange their research subjects, forever after.

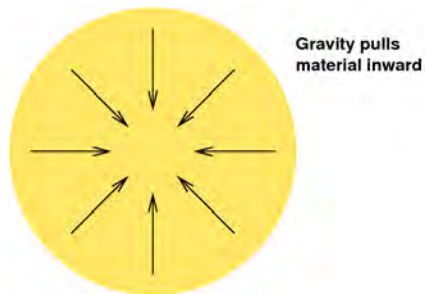
Finkelstein picks up on the combinatorial aspects of quantum spin as a possible route to delving more deeply into the quantum nature of reality and, says Penrose, “took such ideas to greater lengths than anyone else.”

what was ? with early black hole solutions ?

Finkelstein's extension of the Schwarzschild metric provided Penrose with an opening into general relativity, as

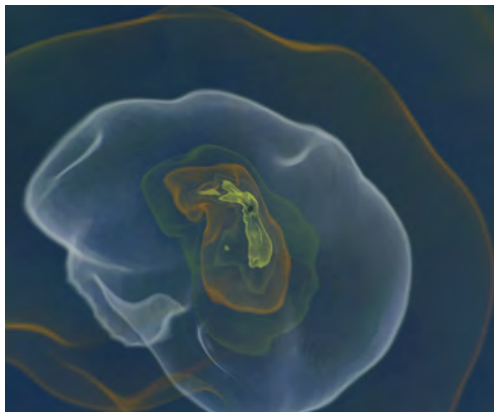
too much symmetry was assumed

how could this **not** lead to a singularity?



age 27 : what if matter sloshes around ?

gaseous collapse into a 10^5 solar mass black hole



Penrose: “Until then, symmetrical singularity collapsed, but asymmetrical could collapse and swirl out.”

simulation : John Wise, Georgia Tech

age 31

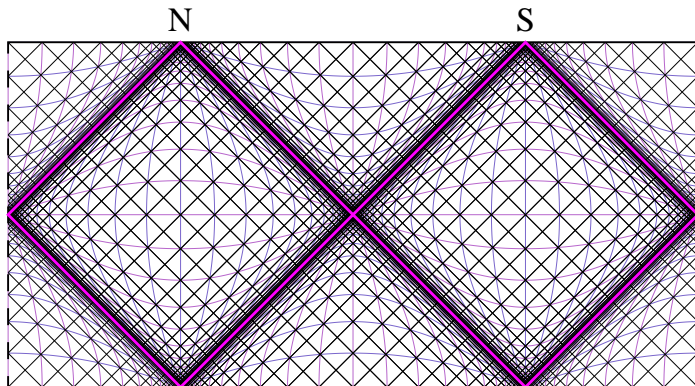


Got a rocket in your pocket? Keep cool, cool, boy!

photo Joan Penrose

age 32 Penrose diagram

regions at infinity placed in a finite position on the causal diagram, so that the entire spacetime can be seen at once



Penrose (conformal) diagram of de Sitter space

age 33 : proves black holes are everywhere using topology

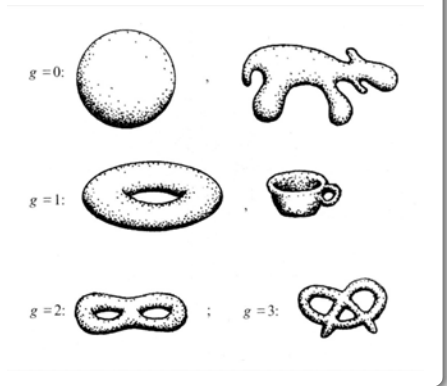
topology is a rubber sheet geometry that deals with

properties of objects when stretched

gravitation **robustly** leads to black hole singularities

new : no need to **solve** equations

“trapped surface of any shape” argument is too subtle for tonight’s story...



Nobel prize paper

VOLUME 14, NUMBER 3

PHYSICAL REVIEW LETTERS

19 JANUARY 1965

GRAVITATIONAL COLLAPSE AND SPACE-TIME SINGULARITIES

Roger Penrose

Department of Mathematics, Birbeck College, London, England
(Received 18 December 1964)

The discovery of the quasistellar radio sources has stimulated renewed interest in the question of gravitational collapse. It has been suggested by some authors¹ that the enormous amounts of energy that these objects apparently emit may result from the collapse of a mass of the order of $(10^6-10^9)M_{\odot}$ to the neighborhood of its Schwarzschild radius, accompanied by a violent release of energy, possibly in the form of gravitational radiation. The detailed math-

measured by local comoving observers, the body passes within its Schwarzschild radius $r = 2m$. [The densities at which this happens need not be enormously high if the total mass is large enough.] To an outside observer the contraction to $r = 2m$ appears to take an infinite time. Nevertheless, the existence of a singularity presents a serious problem for any complete discussion of the physics of the interior region.

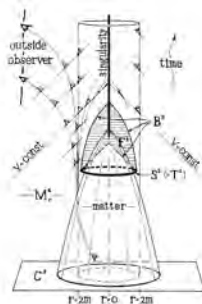


FIG. 1. Spherically symmetrical collapse (see space dimension compressed). The diagram essentially sets scene for the discussion of the gravitational mass.

Done!⁴

can we go home now ?

⁴R. Penrose, Phys. Rev. Lett. 14, 57-59 (1965).



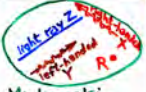
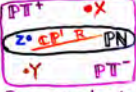

not so fast

took many years for astronomers to become less skeptical

now they are on all board

age 36 invents twistors

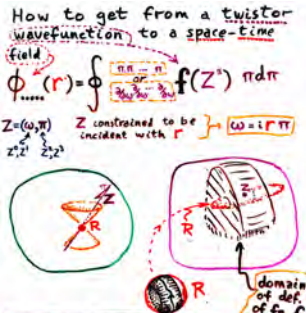
why do we live in 3 space dimensions ?

 <p>light ray Z R = point</p> <p>Space-time</p>	 <p>point Z Riemann sphere R</p> <p>Twistor space</p>
 <p>light ray Z R = point Y X</p> <p>Minkowski space M</p> <p>R has space-time coordinates (r_0, r_1, r_2, r_3)</p>	 <p>PT^+ $\bullet X$ Z^0, CP^1, R, PN $\bullet Y, PT^-$</p> <p>Projective twistor space $PT = CP^3$</p> <p>Z has twistor coordinates (Z^0, Z^1, Z^2, Z^3)</p>
<p>Incidence: $\begin{pmatrix} Z^0 \\ Z^1 \end{pmatrix} = \frac{i}{\sqrt{2}} \begin{pmatrix} r_0 + r_3 & r_1 + i r_2 \\ r_1 - i r_2 & r_0 - r_3 \end{pmatrix} \begin{pmatrix} Z^2 \\ Z^3 \end{pmatrix}$</p> <p>Eqn. of PN: $Z^0 \bar{Z}^2 + Z^1 \bar{Z}^3 + Z^2 \bar{Z}^0 + Z^3 \bar{Z}^1 = 0$</p> 	

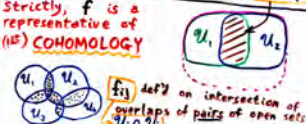
How to get from a twistor wavefunction to a space-time field

$$\phi_{\dots}(r) = \int f(Z^i) \pi d\pi$$

$Z = (\omega, \pi)$ Z constrained to be incident with r $\rightarrow \omega = i r \pi$



Strictly, f is a representative of a $(1,0)$ COHOMOLOGY



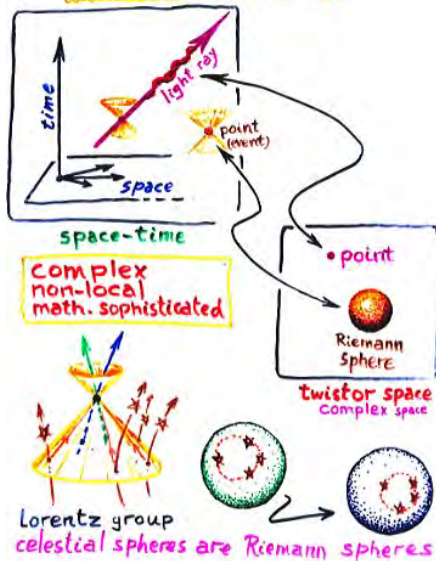
f_{ij} def'd on intersection of overlaps of pairs of open sets $U_i \cap U_j$

our 4-dimensional spacetime is a mirror of a 4-dimensional complex space⁵

⁵R. Penrose, Journal of Mathematical Physics 8, 345-366 (1967).

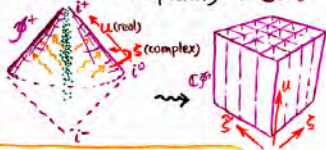
twistors

Twistor Theory



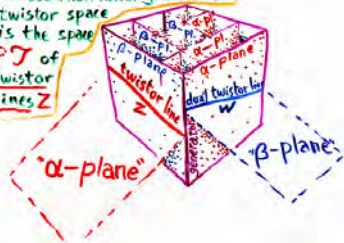
let's twist again

Asymptotic twistors
 \mathcal{M} asymptotically flat, radiating, analytic,
 vacuum: complexify $\rightarrow \mathbb{C}\mathcal{M}$

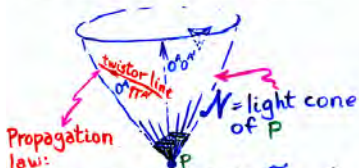


\mathcal{H} -space = ASD "space-time"
 whose ("non-linear graviton")
 twistor space
 is the space

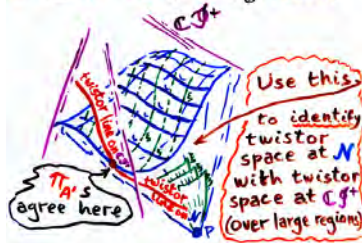
\mathcal{T} of
 twistor
 lines \mathcal{Z}



Null cone of finite point



$$\pi^A \nabla_{\alpha A} \pi_{B'} = \pi_{B'} (\pi_{\alpha'}^{-S} P_{\alpha'} \tilde{\Psi}_{\alpha'0'0'0'})$$



age 38 cosmic censorship / civilization on the edge

gravitational collapse cosmic censorship conjecture

black hole singularities
are confined to an event
horizon

—a “body bag”—

NASA Chandra & NuSTAR
satellite telescopes (2019)



surrounding a hidden space-time region from which a
civilization could harvest energy⁶

⁶R. Penrose, Riv. Nuovo Cimento **Num. Spez. I**, 257 (1969).

age 38 invents negative dimensions

114

ROGER PENROSE

the remaining components being zero. Contraction is represented by the Einstein summation convention in the usual way. Depict:

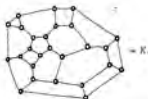
$$t_{ab} = \overset{a}{\curvearrowright} \quad b \quad ; \quad i_{abc} = \overset{a}{\curvearrowright} \overset{b}{\curvearrowright} \overset{c}{\curvearrowright}$$

where the factor $i (= \sqrt{-1})$ is included for simplicity in the signs of reduction formulae. We have, as well-known formulae of tensor calculus, or by repeated applications, thereof:

$$\begin{aligned} 0 &= 1 & \delta &= -1 & \chi &= 1 & \chi &= 1 \\ \chi &= \chi & \chi &= \chi & \chi &= \chi & \chi &= \chi \\ \chi &= \chi & \chi &= \chi & \chi &= \chi & \chi &= \chi \end{aligned}$$

etc.†

Now consider a planar graph of degree three. We can associate with it a certain contracted product of t_{ab} 's, where one t_{ab} is drawn at each vertex, a contraction occurring for each edge of the graph. The result is, for some complex number (actually an integer), K . For example:



The number K is, in fact, precisely the number of ways of colouring the edges of the graph with three colours so that three distinct colours occur at each

*7

life in -2 dimensions

negative two dimensional world is elegant and pretty
(and all calculated by drawings)

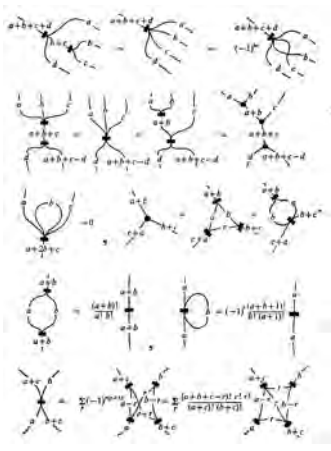
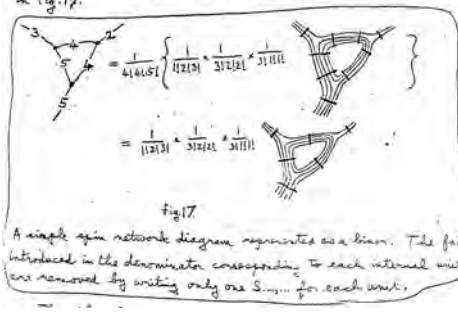
⁷R. Penrose, "Applications of negative dimensional tensors", in *Combinatorial mathematics and its applications*, edited by D. J.A. Welsh (Academic, New York, 1971), pp. 221–244.

age 40 invents spin networks

students ask me : is space continuous or discrete ?

quantum geometry

instead of two (one from each vertex). This is illustrated in fig. 17.

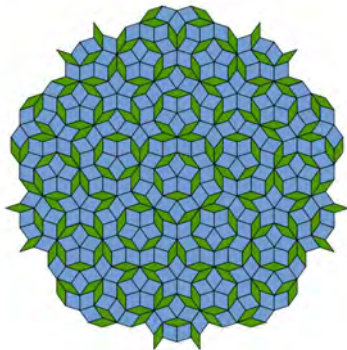


attempt to build our spacetime from quantum spins⁸

⁸R. Penrose, "Angular momentum: An approach to combinatorial space-time", in *Quantum Theory and Beyond*, edited by T. Bastin (Cambridge Univ. Press, Cambridge, 1971).

age 43 invents Penrose tiling

two tiles that tile the plane nonperiodically



with pentagons everywhere⁹

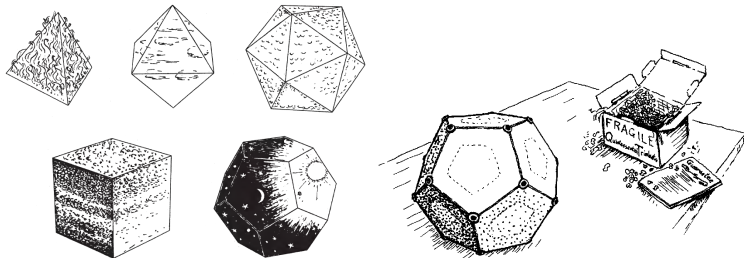
*Google the beautiful Veritasium video :
"The Infinite Pattern That Never Repeats"*

figure Wikipedia

⁹R. Penrose, Bull. Inst. Math. Appl. 10, 266–271 (1974).

Penrose tiling disposes of centuries of hitherto

“forbidden” pentagonal symmetry crystals



completes Kepler's search for pentagonal "snow flakes"
nets a much abused experimentalist a Nobel Prize in chemistry

age any : always contrarian

always needle and irritate fellow physicists

quantum mechanics is **wrong!**

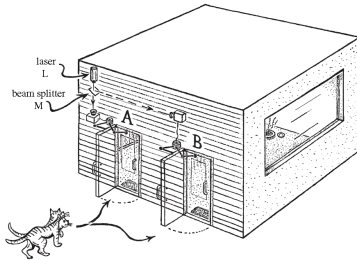
What is missing is gravity :

“gravitization of quantum mechanics” is needed

age any : quantum mechanics is not right

Schrödinger's cat

Schrödinger's cat



classical and/or quantum ?

age any : quantum mechanics' gotta go

Classical Level (C)

Newton, Maxwell, Einstein

Deterministic, Time-Symmetric
(local)

Quantum Level (U)

Schrödinger (unitary evolv.)

Deterministic, Time-Symmetric
(local)

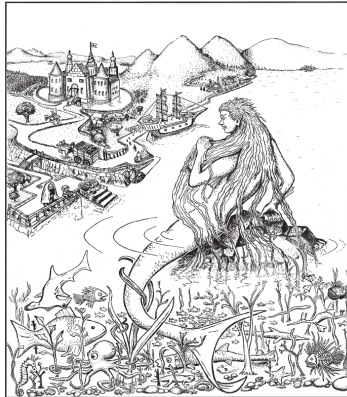
Magnify quantum
event to classical
level

Measurement (R)

Quantum State Reduction
Non-deterministic,
Time-asymmetric
(non-local)

age 58 little Mermaid

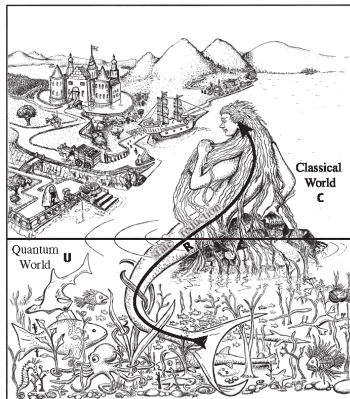
quantum mechanics



classical and quantum

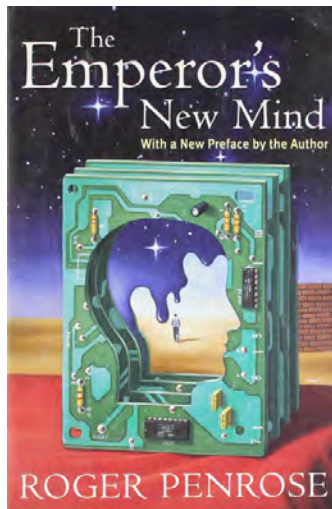
age 58 little Mermaid

quantum mechanics is **wrong**



classical and quantum miss-joined at hip

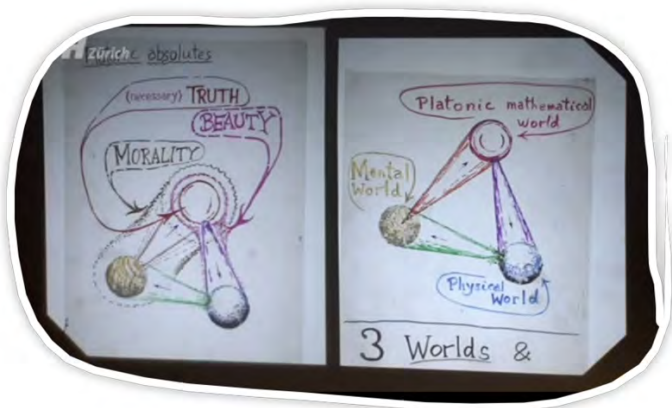
age 58 book *The Emperor's New Mind*



I didn't know much about neuroscience, ...¹⁰

¹⁰R. Penrose, *The Emperor's New Mind, Concerning computers, minds, and the laws of physics*, (Oxford Univ. Press, Oxford UK, 1989).

age 58 Penrose goes New Age on us



argues that quantum mechanics is a fundamental component of consciousness

age 58 New Age full monty

Consciousness:

can we hope to understand it in terms of

1. computation ?
2. existing science ?
3. extended physical world-view ?
4. something beyond science ?

I argue that 3. is what is required.

Arguments from
philosophy
mathematics
physics
biology
psychology

Consciousness has many manifestations

passive: qualia

active: free will

(pain, love, red, pride, determination, intelligence, disgust, will, ...)

I shall concentrate on

UNDERSTANDING

Is a computer, or computer-controlled robot capable of genuine understanding?

intelligence

requires

understanding

requires

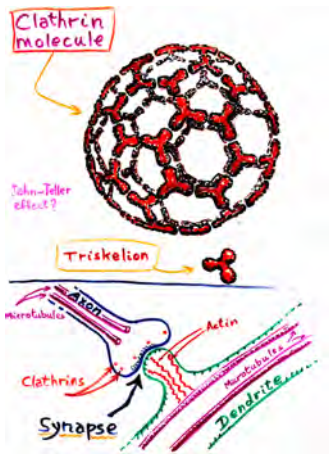
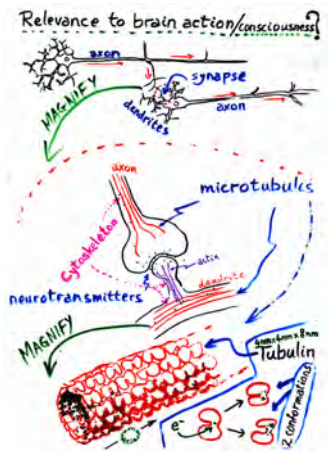
awareness

∴ if understanding can be shown to be beyond computation, then intelligence is not a matter of computation; moreover certain aspects of awareness (perhaps all) are beyond computation also.

“arouses the fury of evolutionary biologists for debunking their ideas about human consciousness”

age 63 book **Shadows of the Mind**

a search for the missing science of consciousness¹¹



with the anaesthesiologist Stuart Hamenoff

¹¹ R. Penrose, *Shadows of the Mind: A Search for the Missing Science of Consciousness*, (Oxford Univ. Press, Oxford UK, 1996).

age 66 sues Kleenex quilted loo paper



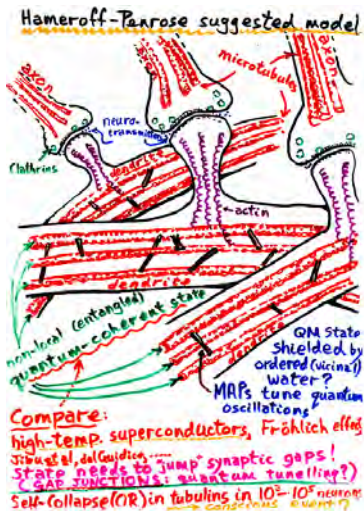
for copyrighted
“Penrose Pattern”

‘I should explain the loo-roll business except I cannot as there was an out-of-court settlement, a condition of which is that I am not allowed to talk about it,’ says Penrose, though his smile suggests there was a happy outcome.

Science Museum Group Collection

age 68 talk Science and the Mind

quantum mechanics of neurophysiology



age 69 collaborative effort with Vanessa Penrose

son Maxwell Penrose

age 73 book *The Road to Reality*

A Complete Guide to the Laws of the Universe¹²

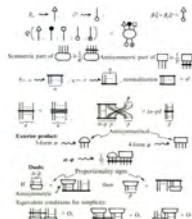
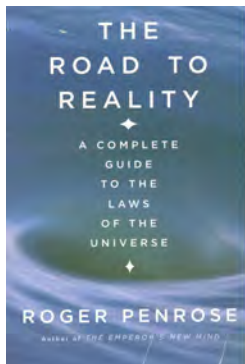
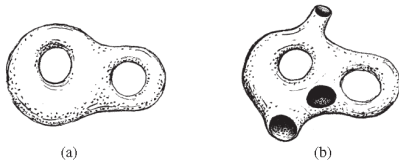
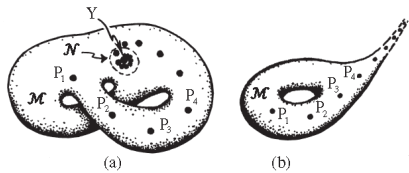
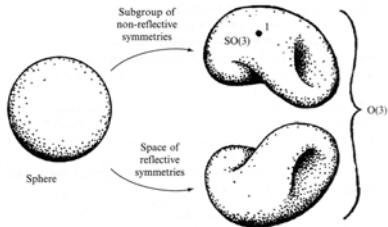
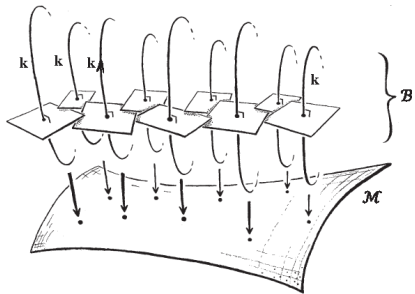
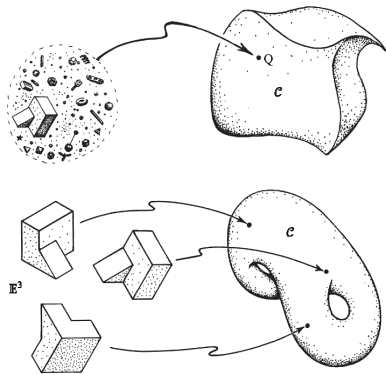
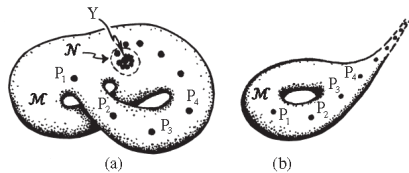
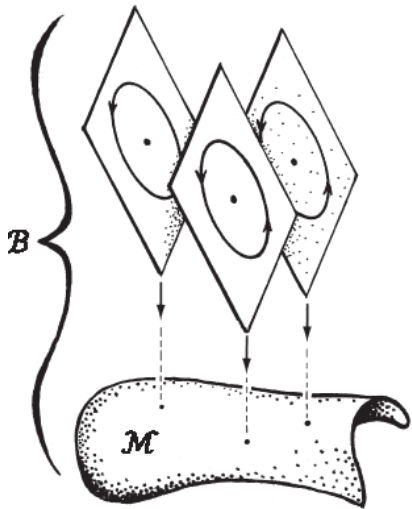


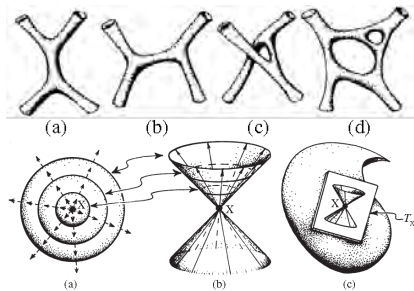
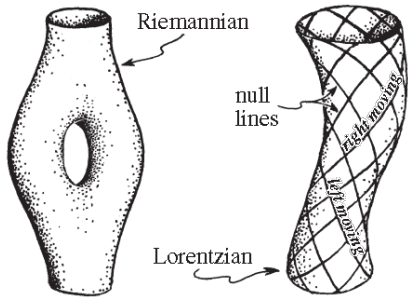
Fig. 12.18 More diagrammatic tensor notation. The diagram for a covector g (1-form) has a single leg, which when joined to the single arm of a vector g gives their scalar product. More generally, the multilinear form defined by a $[p]$ valent tensor Q is represented by joining the p arms to the legs of p variable covectors, and the q legs to the arms of q variable vectors (here $p = 3$ and $q = 2$). Symmetric and antisymmetric parts of general tensors can be expressed using the wavy lines and thick bars of the operations of Fig. 12.17. Also, the bar notation combines with a related diagrammatic notation for the volume n -form $\epsilon_{1\dots n}$ (for an n -dimensional space) and its dual n -vector $\epsilon^{1\dots n}$, normalized according to $\epsilon_{1\dots n} \epsilon^{1\dots n} = n!$. Relations equivalent to $\epsilon^i \epsilon_j = \delta^i_j$ and $\epsilon^i \epsilon_j = \delta^i_j$ to antisymmetrized indices and $\epsilon_{1\dots n} \epsilon^{1\dots n} = n!$ are also represented. Exterior products of forms, the “quality” between p -forms and $q = p$ -vectors, and the conditions for “simplicity” are then succinctly represented diagrammatically. (For exterior derivative diagrams, see Fig. 14.18.)

'Colleagues liked my equations but not the contentious stuff about the mind and urged me to write a straightforward book on physics. I thought it would be a simple scissors job but it didn't work out that way.'

¹²R. Penrose, “Applications of negative dimensional tensors”, in *Combinatorial mathematics and its applications*, edited by D. J.A. Welsh (Academic, New York, 1971), pp. 221–244.





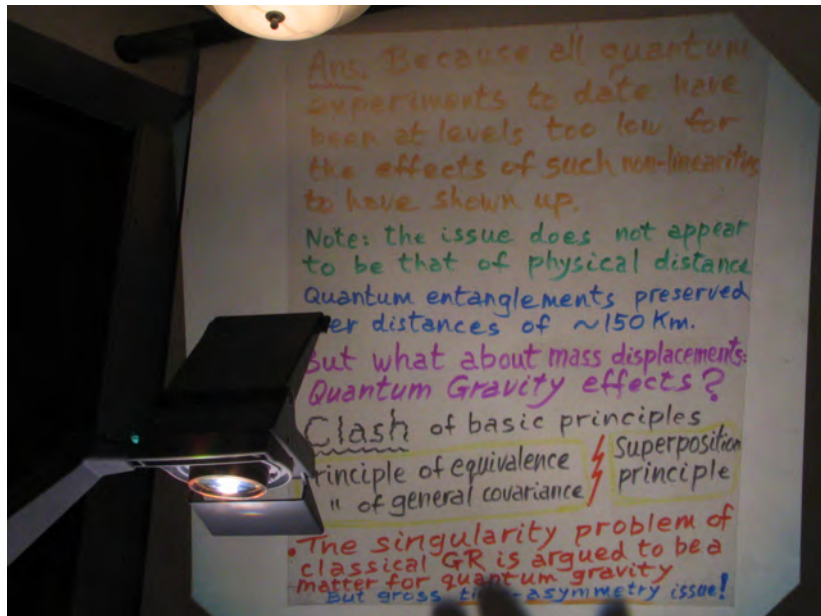


age 75 : Before the Big Bang

an Outrageous Solution to a Profound Cosmological Puzzle

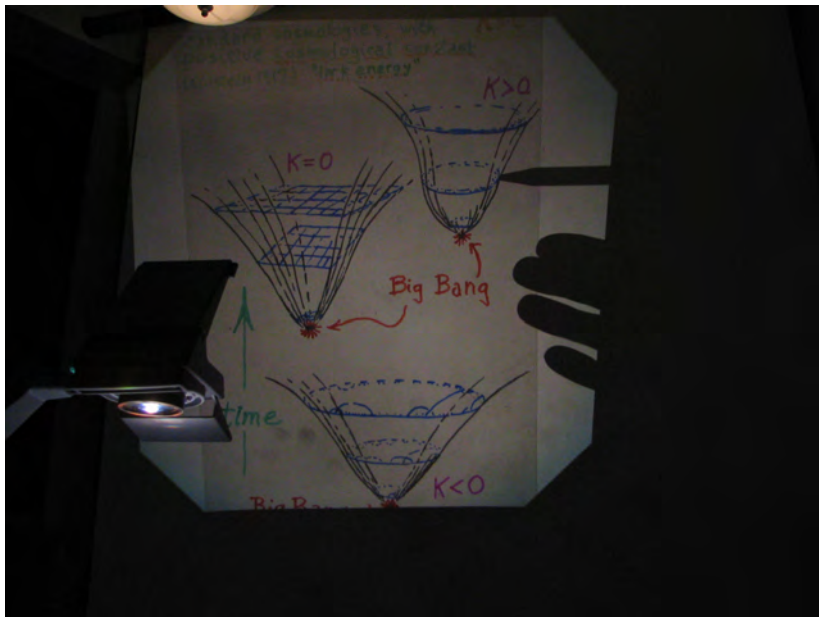


age 75 : a birthday present



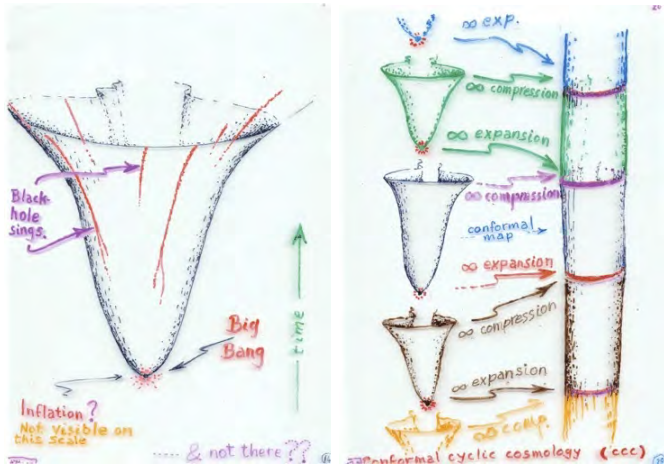
cosmology of eternal rebirth

age 75 : Niels Bohr Institute lecture



we barbarians did not 'get' it ...

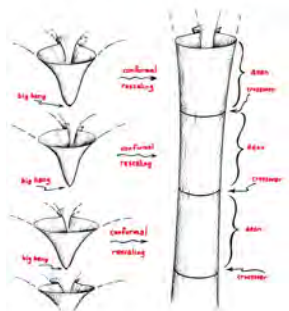
age 75 book : Cycles of Time



*13

age 75 and the bang goes on

evidence of an earlier universe existing before the Big Bang of our own present universe.



The Big Bang is only an apparent singularity, similar to the apparent singularity at the event horizon of a black hole

age 75 : important things first

we barbarians still do not 'get' it ...

Sri Lankan cricket team in England in 2006

From Wikipedia, the free encyclopedia

Sri Lanka toured **England** for **cricket** matches during the **2006 international cricket season** then keep their second place in the ICC Test Championship in India, and the teams were all two lost ODI tours on the Asian sub-continent, against India and Pakistan respectively. To ad their squad for their previous tour and, two days before Sri Lanka departed for England, it wa skip his previous tour too. Jehan Mubarak was brought in as his replacement.

Contents [hide]

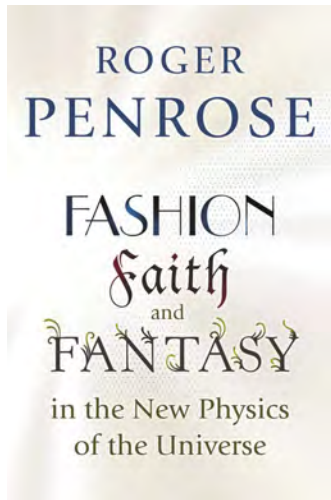
- 1 Schedule
- 2 Squads
- 3 First Class Matches
 - 3.1 Tour Match: Sri Lanka v British Universities (24–26 April)
 - 3.2 Tour Match: Sri Lanka v Derbyshire (29 April–1 May)
 - 3.3 Tour Match: Sri Lanka v England A (4–7 May)
 - 3.4 First Test
 - 3.5 Tour Match: Sri Lanka v Sussex (18–21 May)
 - 3.6 Second Test (25–29 May)
 - 3.7 Third Test (2–5 June)
- 4 Limited Over Matches
 - 4.1 Tour Match: Sri Lanka v Essex (9 June)
 - 4.2 Tour Match: Sri Lanka v Somerset (11 June)
 - 4.3 Twenty20 International Match (15 June)
 - 4.4 First ODI
 - 4.5 Second ODI (20 June)
 - 4.6 Third ODI
 - 4.7 Fourth ODI
 - 4.8 Fifth ODI

G. Gunaratne: “all he would talk about was ...”

How Drawing Is Used for Maths and Science

age 85 book **Fashion, Faith, and Fantasy**

in the New Physics of the Universe¹⁴



¹⁴R. Penrose, *Fashion, Faith, and Fantasy in the New Physics of the Universe*, (Princeton Univ. Press, 2016).

I - as do so many of your friends



love you

and so - back to dreams of reality



with "The Road to Reality" always by my side