Institution: University of Oxford

Unit of Assessment: 10 – Mathematical Sciences

Title of case study: Cycles of Time; Public engagement with conformal infinity

1. Summary of the impact

This case study describes public engagement with the University of Oxford's research in Mathematical Physics via the popularization of science through the writings, public lectures and media appearances of Sir Roger Penrose. Published in 2010, Penrose's book *Cycles of Time* deals directly with the research contributions and has reached broad audiences via books, public lectures, TV appearances, and YouTube postings. The impact has been to engage large numbers of the public with modern theories of the origin of the universe in a mathematically non-trival way.

2. Underpinning research

In 1999, Professor Paul Tod, faculty member at Oxford University, published [1,2] a mathematical study of Penrose's Weyl curvature hypothesis as described in [3], giving a rigorous analytic treatment of solutions to the partial differential equations at an initial singularity and an optimal geometric framework for their study. Tod gave a definitive statement of the Weyl curvature hypothesis and showed that it could be re-framed as the condition that the conformal structure of space-time can be smoothly continued through an initial singularity. This gives a clear mathematical meaning to 'the universe before the big bang' and underpins Penrose's subsequent proposals for the nature of physics before the big bang.

The singularity theorems imply that there must have been an initial singularity, the big bang, approximately 14 billion years ago, in which the universe that we see started essentially from a point. This is now an integral part of the standard modern view of our universe. The existence of the big bang invites questions such as: What controlled the big bang? Did anything precede it? If so, what? A theme emphasized by Penrose is that the second law of thermodynamics provides overwhelming evidence for special initial conditions for the evolution of the universe; he proposed the Weyl curvature hypothesis, namely that the 'Weil curvature' should vanish as the initial singularity is approached. With this assumption, Tod's work demonstrated that it is meaningful to continue the conformal geometry of the universe back in time to before the big bang [4].

Penrose's concept of conformal infinity gives a geometric realization to those events that occur at infinitely late times, exploiting an analogy with the perspective ideas of projective geometry as a surface at infinity whose conformal structure again has a smooth continuation through infinity. More recently, Nobel prize winning studies of observational data showed that the universe is controlled by a positive cosmological constant (also known as accelerated expansion or dark energy). Penrose observed that with such a positive cosmological constant, conformal infinity has the same conformal geometry as the big bang in Tod's work. This led him to propose that the big bang is conformally glued to the future infinity of a previous aeon or epoch of the universe with positive cosmological constant [3], answering the question as to what precedes the big bang. Two consecutive aeons are separated by infinite time and massive particles cannot communicate from one aeon to the next. However, massless particles such as photons or gravitational waves continue through from one aeon to the next leading to observable consequences. The paper [5] was the first announcement of the new conformally cyclic cosmology proposals.

Key researchers from the University of Oxford

K.P. Tod: University Lecturer at the Mathematical Institute, 1985-date.
R. Penrose: Rouse-Ball Professor at the Mathematical Institute 1973-1998, subsequently retired but working in the Mathematical Institute as an emeritus Professor.

3. References to the research

*[1] K. Anguige and K.P. Tod, “Isotropic cosmological singularities. 1. Polytropic perfect fluid space-times,'' *Annals Phys*., 276 (1999) 257 [gr-qc/9903008], 29 citations. DOI: 10.1006/aphy.1999.5946

*[2] K. Anguige and K.P. Tod,”Isotropic cosmological singularities. 2. The Einstein-Vlasov system,'' *Annals Phys*., 276, (1999) 294 [gr-qc/9903009], 16 citations. DOI: 10.1006/aphy.1999.5947

[3] S Hawking and R Penrose, the Nature of Space and Time, New Edition, Princeton University Press (April 01, 2010) ISBN: 9780691145709. Originally published in 1997.

*[4] K.P. Tod,”Isotropic cosmological singularities in spatially-homogeneous models with a cosmological constant,'' *Class. Quant. Grav*., 24, (2007) 2415 [arXiv:0704.2506 [gr-qc]]. DOI:10.1088/0264-9381/24/9/017

[5] R.Penrose, “Before the big bang: An outrageous new perspective and its implications for particle physics,'' *Conf. Proc. C* 060626, (2006) 2759. Journal article available at http://accelconf.web.cern.ch/AccelConf/e06/PAPERS/THESPA01.PDF.

The three asterisked outputs best indicate the quality of the underpinning research and are contained in high quality internationally refereed journals.

4. Details of the impact

The impact is on society through public interest and engagement with science and the stimulation of public discourse. The questions of the ‘origin of the universe', ‘what happened before the big bang?', and ‘how space-time might emerge from a more fundamental theory’ are some of the most frequently addressed issues in popular science and stimulate wide interest (and controversy). Roger Penrose's writings have opened up new avenues in this debate that have led to much interest outside academia. The beneficiaries since 2008 have been the general public who gain an understanding of current models for the evolution of the universe.

The research of Paul Tod demonstrated rigorously that the Weyl curvature hypothesis gave mathematical sense to the question of whether the conformal geometry whose existence is demonstrated mathematically has any physical meaning. This underpinned Penrose’s Conformally Cyclic Cosmology proposal. His recent broad audience book *Cycles of Time: An Extraordinary New View of the Universe* (published in 2010) explains the conformal cyclic cosmology which is underpinned by the research described in Section 2.

Cycles of Time has been hugely successful. More than 95,000 copies have been sold worldwide since 2010 [A], it has been translated into German, Polish, Italian and Russian, and released as an audio book. *The Nature of Space and Time* has sold 10,502 copies in the period [B] and the *Road to Reality*, another pre-cursor building on the themes in the Nature of Space and Time, has sold nearly 120,000 copies since 2004 including 45,400 in the REF period [A]. The books are also promoted with accompanying public presentations at large book fairs (e.g., 25/11/10 at Toppings, The Paragon, Bath, Somerset or 26/3/12 Sunday Times Literary Festival, Oxford). A new book by Penrose is an automatic choice for review in quality media of all kinds.

Penrose’s books are highly unusual among popular science books in celebrating rather than obscuring the mathematical equations and geometrical pictures that underlie the physical ideas. They take the audience seriously as intellectuals and do not oversimplify. Readers engage directly with Penrose’s writing, as evidenced by a 2008 reader review [C] of *The Road to Reality* on Amazon: “*If you assiduously go through every sentence until you understand its meaning, if you consult outside references as necessary, if you really absorb this material- it is phenomenal. Penrose will equip you with a visual and intuitive comprehension of the advanced math necessary to really understand the big theories of physics.* [...] *In terms of the breadth and scope, I could compare this to the Feynman lectures.* [...] *This is a book to live in for a long time. There is nothing else quite like it. The rewards justify the large amount of reader time and effort that will need to be committed.*

Five stars, absolutely". Professional and reader reviews of *Cycles of Time* also attest to Penrose's success in engaging with the wider public:

"*The most influential person to develop the general theory of relativity since Einstein*" [D]

"*A gifted popularizer of science* […] *Roger Penrose has attracted a popular audience with thought-provoking books on physics, consciousness and the theory of computation"* [E]

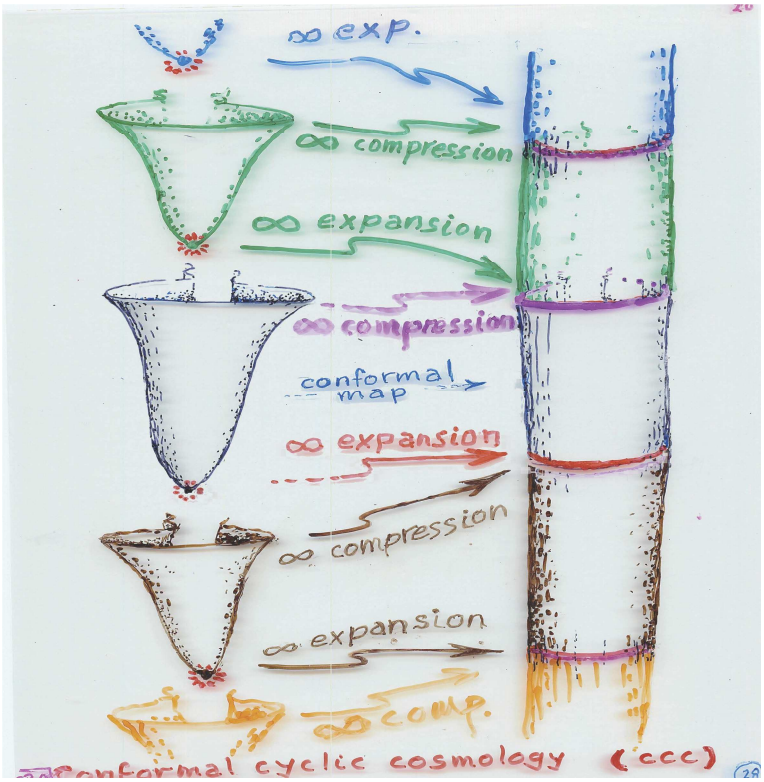
"*Doing what most find impossible has long been Penrose's stock in trade in mathematics and physics, even when it comes to publishing*" [F]

"*One of the world's best science writers*" [G]

"*As usual, one gets a clear, simply, but new view of physics from Penrose. The depth is much greater than many popular science books, but I find I can grasp the ideas. I have wondered for a long time how to get an understanding of metrics which seem all important in modern physics. I looked at a collection of math books which would provide the knowledge but felt that it would take the rest of my life to get there. Penrose gave me as much knowledge of the ideas and usage of the methods as I need in one* page" [H]

This approach makes his contributions to the public engagement with science particularly important as it allows the public to see scientific debate as a rigorous evaluation of mathematical argument and empirical data rather than as 'anything-goes' speculation with one person's theory being on a democratic footing with anyone else's.

Another unusual feature of Penrose's public engagement is that he is rarely reviews other people's ideas except to counterpoint them against his own. He engages people directly with his own research and that of his close associates following the programmes that he has initiated. The public engagement described in this study arises directly from the research described here and not from that of others or older ideas. This point is reinforced by his use of hand-drawn diagrams which have attracted much favourable comment from readers of his books and online viewers of his lectures, for example *"He's probably the only world famous speaker that draws his own slides with color marker pens! Not just a brilliant mind but also a talented illustrator!"* comments one YouTube watcher in 2011 [I].



The wide impact of these ideas and Penrose's presentational style is evidenced by regular invitations to give distinguished public lectures and to appear on the media the world over. Penrose featured prominently in a 2010 BBC *Horizon* programme which attracted more than 1.8 million viewers [J]. His public lectures typically pack out the largest available auditoria, sometimes with overflow rooms equipped with video-links. For example, a capacity audience of 477 saw him at the Royal Institution in 2010 [K], while an audience of more than 700 saw him lecture after receiving the 2011 Fonseca prize. Of those who filled in a feedback questionnaire following the Royal Institution lecture, 94% had come 'to find out more' and 82% wanted 'to find out more following the event' [K]. He gave the Tagore, Bose and Chandrasekhar memorial lectures in Kolkata, the Chandrasekhar lecture Delhi, the Neils Bohr lecture in Copenhagen, the Trotter Public lecture after receipt of the Trotter prize at Texas A&M, and the Copernicus Institute Lecture in Warsaw among many others

around the world.

The impact of Penrose's public lectures is not limited to the few hundred people that attend each of them, as they are often filmed and posted online. For example, YouTube lists 344 videos in response to a search for 'Roger Penrose'; not all of these feature him directly, but total views of those that do, and were posted since 2008, number well over 500,000 [L]. A good example is his 2009 Christmas Lecture *Aeons before the Big Bang* with more than 52,000 views [M]; another is his 2010 TEDx lecture aimed at encouraging young people to engage with STEM subjects, with more than 32,000 views [N]; and a third is a public lecture on *Twistors and Quantum non-locality*, broadcast on TV in Ontario in 2011, with more than 40,000 views [O]. Many of the posted videos generate comments numbering in the hundreds and often stimulate online dialogues about the content of the lectures.

These are outstanding impacts on a world stage. As can be seen, Penrose is in great demand and has a worldwide following.

5. Sources to corroborate the impact

[A] Email from Literary Consultant, The Zeno Agency, confirming sales numbers for the books of Roger Penrose, copy held by the University of Oxford.

[B] Email from Executive Editor, Princeton University Press, confirming sales numbers for *The Nature of Space and Time*, copy held by the University of Oxford.

[C] Reader review at http://www.amazon.co.uk/review/R2SS0HKLRGGNT9/ref=cm_cr_pr_perm?ie=UTF8&ASIN=0099440687&linkCode=&nodeID=&tag=

[D] Review in Nature of *Cycles of Time* http://www.nature.com/nature/journal/v467/n7319/full/4671034a.html.

[E] Review in The Wall Street Journal of *Cycles of Time* http://online.wsj.com/article/SB10001424052748703730804576317072124312488.html

[F] Review in The Guardian of *Cycles of Time* http://www.guardian.co.uk/books/2010/oct/16/cycles-time-roger-penrose-review.

[G] Review in The New York Journal of Books of *Cycles of Time* http://www.nyjournalofbooks.com/review/cycles-time-extraordinary-new-view-universe

[H] Reader review at http://www.amazon.co.uk/review/R1PWAJGLN1V1U6/ref=cm_cr_pr_perm?ie=UTF8&ASIN=0224080369&linkCode=&nodeID=&tag=

[I] Viewer review at http://www.youtube.com/watch?v=oBkOYQ02chs:

[J] Horizon, Before the Big Bang, 11 October 2010, BBC2, over 1.82 million viewers, http://www.bbc.co.uk/programmes/b00vdkmj, number of viewers found on www.barb.co.uk

[K] Email from Public Programme Manager at the Royal Institution. Contact details held by the University of Oxford.

[L] Viewing figures for Penrose videos on youtube: www.youtube.com/results?search_sort=video_view_count&search_query=roger+penrose

[M] Aeons Before the Big-Bang, Sir Roger Penrose Christmas Lecture, December 2009, http://www.youtube.com/watch?v=OutKE3tyG94

[N] Space-Time Geometry and a New Cosmology, 6 March 2010 TEDx, Warwick University, http://www.youtube.com/watch?v=oBkOYQ02chs. TEDX organisers. Contact details held by the University of Oxford.

[O] Twistors and Quantum Non-Locality, Public Lecture and broadcast on TV Ontario, 6 April 2011, Ontario Canada, at http://www.youtube.com/watch?v=hAWyex1GKRU

[C]-[I] exemplify the significance of the public engagement activities; [J]-[O] exemplify the reach.