

Institution: University of Cambridge		
Unit of Assessment: 10 Mathematics		
Title of case study: Black Holes and the Early Universe: advancing the public's interest and understanding of our Universe		
Period when the underpinning research was undertaken: 1/1/2000 – 14/3/2018		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): Professor Stephen Hawking	Role(s) (e.g. job title): Director of Research, Centre for Theoretical Cosmology (CTC), Faculty of Mathematics	Period(s) employed by submitting HEI: 1/10/1975 – 14/3/2018
Period when the claimed impact occurred: 1/8/2013 – 31/7/2020		
Is this case study continued from a case study submitted in 2014? N		
1. Summary of the impact (indicative maximum 100 words)		
<p>[I1] Professor Stephen Hawking could be the best-known scientist of his generation, known by 99% of the UK adult population. He stimulated public interest in science and increased his audiences' understanding of fundamental scientific research. His public lectures, books, TV, film and social media, allowed millions of people from all educational backgrounds to engage with his research, inspiring wonder, curiosity and provoking debate about the fundamental nature of the Universe. For example, his 75th birthday symposium reached over 5.4 million people worldwide.</p> <p>[I2] Hawking's research was the basis for numerous commercial partnerships with the creative sector. In the REF period, his books sold an estimated 3.6 million copies with an estimated sale value in excess of GBP30,000,000 and his collaboration on a Discovery TV series led to the employment of at least 50 people.</p>		
2. Underpinning research (indicative maximum 500 words)		
The Black Hole Information Paradox		
<p>According to the quantum mechanics, information cannot be destroyed; it can only be transformed from one form into another. Therefore, what happens to the information (e.g. about shape, size, chemical composition) of an object that falls into a black hole? The <i>no hair theorem</i> (proved in the 1970s by Hawking and colleagues), says that all we can know about a black hole is its total mass, spin and electric charge, and these pieces of information give nothing away about the details of the objects that might have fallen into it.</p> <p>In 1976, Hawking proved that black holes do emit thermal radiation, but the no hair theorem implies that the information contained in this Hawking radiation is again independent of any objects the black hole had devoured. This is the <i>information paradox</i>: after the black hole has evaporated through Hawking radiation, what happened to all the information from the objects that fell into it?</p> <p>Since 2000, Hawking, using discoveries from string theory, argued that the information was not lost, and could escape the black hole in a mangled form: "<i>It is like burning an encyclopedia. Information is not lost, if one keeps the smoke and the ashes. But it is difficult to read</i>" [R1]. However, how the information was preserved remained mysterious. In 2016 and 2017 Hawking, collaborating with Professors Strominger (Harvard) and Perry (Cambridge), realised that the way the no hair theorem was formulated was too restrictive [R2, R3]. They argued that the information about the material that formed the black hole</p>		

remains preserved as *supertranslation* and *superrotation hair* on the horizon of the black hole. This would then be imprinted on the Hawking radiation. One could then recover information about the initial state from this radiation.

This work constitutes a major step towards the resolution of the information paradox – which would be an important advance towards formulating a theory of quantum gravity.

The No Boundary Proposal

Hawking's most daring project has been quantum cosmology and his *No Boundary Proposal* for the Universe (NBP). This describes what happened at the Big Bang, which Einstein's theory of relativity cannot describe. Developed in the 1980s with Professor Hartle (University of California), the proposal says that when we go back toward the beginning of our Universe, space and time become fuzzy and "cap off", somewhat similar to the way the direction North ceases to be well defined at the North Pole.

Since 2000 Hawking, Hartle and Professor Hertog (KU Leuven) have been exploring what predictive powers the NBP can bring to cosmology. They calculated what kinds of universe could emerge from the Big Bang according to the proposal [R4, R5, R6], and the observational consequences. They argued that the NBP predicts a universe that begins with a period of *inflation* (exponential expansion). The universe would start almost completely smooth, apart from small quantum irregularities that would be expanded by inflation to give rise to all the structure we see in the Universe today. Some of these predictions are now being tested, others, such as the production of primordial gravitational waves during inflation, can be tested by future observations.

Recently Hawking and Hertog studied eternal inflation from a different viewpoint, based on string theory and a concept called holography. The NBP predicts that many different universes can emerge from the quantum fuzz of the Big Bang. However, these are overwhelmingly likely to be smooth, and finite, in contrast with the infinite fractal-like multiverses arising from other theories of eternal inflation [R7].

The No Boundary Proposal remains the leading candidate for a theoretical description of the birth of the Universe.

The wider public has long held a fascination with black holes and the universe, Hawking drew on his research to inform and disseminate information to the public, satisfying curiosity and leading to a greater interest in science.

3. References to the research (indicative maximum of six references)

- [R1] Information loss in black holes. S.W. Hawking, Phys. Rev. D, 2005, 72 (8), 084013. arXiv:hep-th/0507171, DOI:10.1103/PhysRevD.72.084013
- [R2] Soft Hair on Black Holes. S.W. Hawking, M.J. Perry and A. Strominger, Phys. Rev. Lett., 2016, 116 (23), 231301. arXiv:1601.00921, DOI:10.1103/PhysRevLett.116.231301
- [R3] Superrotation charge and supertranslation hair on black holes. S.W. Hawking, M.J. Perry and A. Strominger, J. High Energ. Phys., 2017, 161 (2017). arXiv:1611.09175[hep-th], DOI:10.1007/JHEP05(2017)161
- [R4] Populating the landscape: A top-down approach. S.W. Hawking and Thomas Hertog, Phys. Rev. D, 2006, 73 (12), 123527. arXiv:hep-th/0602091, DOI:10.1103/PhysRevD.73.123527
- [R5] No-Boundary Measure of the Universe. James B. Hartle, S.W. Hawking and Thomas Hertog, Phys. Rev. Lett., 2008, 100 (20), 201301. arXiv:0711.4630 [hep-th], DOI: 10.1103/PhysRevLett.100.201301

[R6] Classical universes of the no-boundary quantum state. James B. Hartle, S.W. Hawking and Thomas Hertog, Phys. Rev. D, 2008, 77(12), 123537. arXiv:0803.1663 [hep-th], DOI:10.1103/PhysRevD.77.123537

[R7] A smooth exit from eternal inflation? S.W. Hawking and T. Hertog, J. High Energy Phys., 2018, 147 (2018) arXiv:1707.07702 [hep-th], DOI:10.1007/JHEP04(2018)147

All outputs have been published in peer-reviewed journals.

4. Details of the impact (indicative maximum 750 words)

[I1] Hawking's ability to share his research with people of all ages and educational backgrounds stimulated public interest and increased understanding of fundamental scientific research.

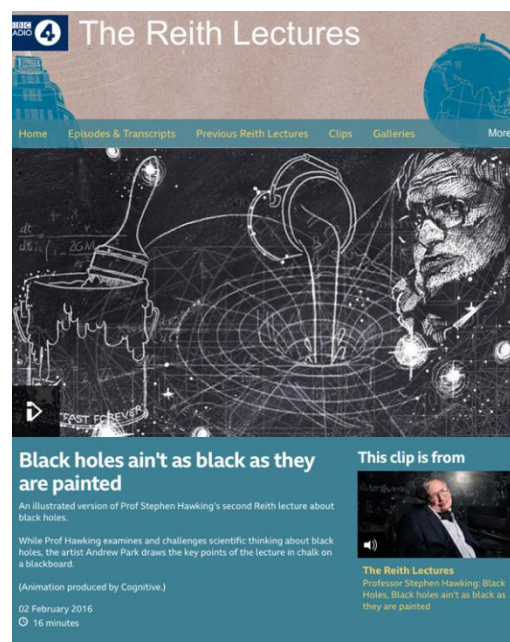
In a December 2019 YouGov survey of a representative sample of over 2000 UK adult respondents, 99% had heard of Hawking and 53% of those aged 18-24 reported that learning about Hawking and his research increased their understanding of the Universe. Similarly, 39% of all respondents were more interested in science and technology as a consequence. For those aged 18-24 who have benefitted from Hawking's most recent public engagement work, 23% were encouraged to study science and technology at school and/or university [E1].

The Reith lectures and the information paradox

Hawking's research actively engaged those typically uninterested in science, together with those more scientifically invested, as shown by his 2016 BBC Radio 4 Reith Lectures. Hawking led the audience through the history of black hole research, right up to his recent work with Perry and Strominger on the information paradox [R1, R2, R3]. An unprecedented 25,000 people applied for tickets, and hundreds of questions were submitted for the Q&A sessions [E2]. These came from a wide cross-section of the public, including a 12-year-old school student and a self-described "ordinary working bloke" [E3].

The lectures reached over 4 million people via Radio 4 broadcast and website. They were downloaded several hundred thousand times from the BBC iPlayer and aired on the BBC World Service [E2]. The book and e-book of the lectures were released in May 2016 and sold over 105,000 copies [E4]. Over a fifth (22%) of UK adults were aware of these lectures either via broadcast, online or through the book [E1]. Over half of the book reviews on Amazon and Goodreads reported that it stimulated readers' interest and increased their understanding of the research [E5]. These reviews show Hawking's research reached an audience who would not normally engage with this type of scientific research:

"...through his brilliant, easy to read and understand authorship, people like me, an 87 years old lady, are able to 'See' into and through time and space" – review on Amazon.co.uk



Hawking's Reith lectures, available online from the BBC

Facebook, YouTube and the No Boundary Proposal (NBP)

One of his last Facebook posts (7 Nov 2017), demonstrates the impact of Hawking's communication of his recent research on NBP. It reached over 2.1 million people with over 100,000 clicks, 30,000 reactions, 2,600 comments and 8,100 shares [E6]. This post linked to a YouTube interview with Hawking, Hartle and Hertog guiding over 600,000 viewers through NBP, its observational consequences [R4, R5, R6] and explicitly explaining their recent work published in July 2017 [R7].

Comments on the Facebook post and YouTube video demonstrate that the research engaged the widest possible audience, including an 8th grade school student, the (self-confessed) math-impaired and a middle-aged housewife [E5].

"Thanks so much for this film - I'm a middle age housewife, and I can't do math, but even I can understand your film and explanation of the No Boundary Proposal (good job!)" – comment on YouTube

75th Birthday symposium

Hawking's 75th birthday symposium in July 2017 included a series of public lectures livestreamed by *Discovery Science* on YouTube and Facebook, which reached over 5.4 million people worldwide [E7] and conveyed the motivation and excitement of his recent work on the information paradox [R2, R3]. An overview of his work on quantum gravity [R1] and NBP [R4, R5, R6] provided a direct link between the research being discussed at the scientific meeting and online public audiences, both directly and through extensive media coverage (including various BBC channels and website; Time magazine; The Telegraph, The Times and Daily Mail newspapers) [E7, E8].

The Vice-President for Editorial Development for Europe, Middle East and Africa, from Discovery, said that this collaboration helped Discovery achieve its key goal to bring science to younger audiences, increasing their interest. A quarter of viewers on YouTube and Facebook were aged 18-24, and 31% of viewers on Facebook and 43% of those on YouTube were aged 25-34. *"Also, the engagement figures were particularly positive with 72% of the viewers actively sharing the content with their own social networks, showing that, once again, Professor Hawking's research [...] gave them a new and deeper understanding of the Universe."* [E7]



Livestreaming of Hawking's 75th birthday lecture

[I2] Hawking's communication of his research resulted in clear economic impact through book sales, commercial partnerships and investment in his media collaborations.

Between January 2013 and May 2020, Hawking's nine books sold over 3.8 million copies, equating to around 3.6 million copies between August 2013 and May 2020. The estimated sale value was in excess of GBP30,000,000 [E4]. Hawking's last book, *Brief Answers to Big Questions*, featured his recent research on the information paradox [R2, R3, R4, R5, R6].

The hardback and e-book were released October 2018, followed by the paperback in March 2020, with combined sales of over 1.3 million copies.

Hawking collaborated with Discovery since 2010. Ten Discovery employees worked on the live stream of Hawking's 75th birthday symposium in 2017. A direct consequence of this successful collaboration is a 25-part TV series (in production) which brings Hawking's latest research [R1, R2, R3], and current research of CTC members, to a younger audience. Since April 2019, a core group of five Discovery employees have been working on the series. Discovery have invested around [Text redacted for publication] in commissioning the production company Navada [E7]. Since April 2019 Navada have employed 12 people working internally on the series, and a further 28 working freelance [E9].

The CTC continues Hawking's legacy, engaging young people around the world with the excitement of fundamental scientific research.

5. Sources to corroborate the impact (indicative maximum of 10 references)

- [E1] Survey through the YouGov GB/UK Omnibus panel, run 18-19 December 2019
- [E2] Letter from Head of Radio Current Affairs at the BBC, 10 March 2020
- [E3] Annotated transcripts of first BBC Reith Lecture with Q&A
- [E4] Letter from United Agents, 27 May 2020
- [E5] Survey of comments and reviews from online sources, compiled by Hannah Banks, PhD student in DAMTP between Dec 2019 and Jan 2020
- [E6] Report of online statistics, including website and social media stats, collated by Jon Wood, Technical Assistant to Professor Stephen Hawking, 31 Aug 2018
- [E7] Letter from VP Editorial Development for Europe, Middle East and Africa, Discovery Channel, 4 April 2020. **CONFIDENTIAL**
- [E8] 2015-2017 Reports to Avery-Tsui Foundation on Stephen W. Hawking Professorship of Cosmology
- [E9] Letter from CEO, Navada, 5 March 2020