Stephen Hawking (1942–2018)*

Rajesh Gopakumar and Spenta R. Wadia

Biographical Details

Stephen Hawking, born on 8 January 1942, at Oxford in an academic family, had an early aptitude and inclination towards science. He studied physics and chemistry at the university in Oxford, though he seems not to have excelled as a student, instead spending much of his time at the college boat club! He went to Cambridge for his PhD hoping to study cosmology with Fred Hoyle, but instead was assigned to Dennis Sciama who proved to be an important influence on him. It was at this time that Hawking was diagnosed with ALS or Lou Gehrig's disease – a degenerative motor neuronal disorder. Though he was given only a couple of years to live at age 22 or so, his disease progressed slower than predicted. Hawking overcame an initial depression to plunge fully into his research soon making a mark for himself, winning the prestigious Adams Prize in 1966, for his thesis work on singularities in Einstein's theory of gravity. He remained at Cambridge as a Fellow of Caius and Gonville College for much of his research career, except for a stint as the Sherman Fairchild Distinguished Professor at Caltech, USA, from 1970 to 1975. He was elected at age 32 as a Fellow of the Royal Society of London and in 1979 appointed to the celebrated Lucasian Professorship of Mathematics (held by Newton, Babbage, Dirac and others) at Cambridge. He held this post till his retirement in 2009. Despite a progressive loss of his motor abilities and being increasingly confined to his wheelchair and later forced to communicate through

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a voice synthesizer, he maintained a remarkably productive scientific career which continued with research publications almost till a few months before his demise on 14 March 2018.

Below we first sketch the important scientific contributions by Hawking, hoping to convey to a broad scientific audience the pathbreaking nature of his discoveries. We also maintain that a fuller understanding of his scientific legacy and in particular, the lasting impact of his work is best brought out by placing it in the broader context of current research on some of the questions that were at the heart of Hawking's quest.

With hindsight, it might appear that there had been a grand and premeditated design to address the outstanding problems concerning the origin and evolution of the universe. But it was not really like that. I did not have a master plan; rather I followed my nose and did whatever looked interesting and possible at the time.

–Stephen Hawking

Major Scientific Contributions

In a foreword in 1993, to a collection of his papers, Hawking [1] writes 'With hindsight, it might appear that there had been a grand and premeditated design to address the outstanding problems concerning the origin and evolution of the universe. But it was not really like that. I did not have a master plan; rather I followed my nose and did whatever looked interesting and possible at the time.' However, it is striking to see the coherence of ideas as well as steady progression of thinking in Hawking's work. Scientifically, the most productive period of his life was from the late sixties through the mid-late eighties, peaking with the remarkable discoveries of the mid-seventies that he is most celebrated for. In this section, we trace this trajectory with broad brushstrokes. It begins with his fundamental work on singularities in the classical Einstein's theory of general relativity in the sixties. This leads to pioneering work on general properties of black holes, at first in the classical theory, but eventually incorporating quantum effects and raising the conundrums that have not been fully resolved to this day. Realizing that these effects might also be present in the early universe led to insights on how these small fluctuations are eventually responsible for structure formation at the largest scales. This, in turn, led to wrestling with the really difficult problems of quantum gravity, i.e. the quantum fluctuations of space–time itself. The striking proposals on the wave function of the universe and related approaches to avoiding the singularities associated with the big bang, while incomplete in themselves, ultimately may well be embedded in a full-fledged understanding of quantum cosmology.

The singularity theorems

Many of the known (and physically interesting) exact gravitational solutions of the Einstein equations possess what is known as a singularity. This is a region of space–time beyond which it cannot be continued because the curvature (which is a measure of the strength of the gravitational field) goes to infinity or 'blows up'. Associated physical quantities like density and pressure also blow up. This is also a signal of the breakdown of predictability of the classical Einsteinian description. The solutions which exhibit such behaviour include the Robertson–Walker metric for describing the expanding universe, the Schwarzschild and Kerr solutions for describing spherically symmetric and rotating black holes respectively, etc. In the sixties there was a dominant school

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of thinking which felt these singularities were artifacts of highly symmetric solutions which would not be present in more generic, realistic cases. However, in a series of papers, Roger Penrose, employing novel mathematical techniques began to question this dogma at least in the context of black holes formed from collapsing matter. Hawking (together with George Ellis, initially) tried to adapt these to the cosmological setting.

Hawking–Penrose result helped to not only settle the controversy on singularities, but also highlighted the power of the new techniques of global analysis that were brought to bear. These continue to play an influential role in classical general relativity and the textbook by Hawking and Ellis which approached the subject from this point of view is now a classic.

The work culminated in a general result by Hawking and Penrose (1970), who showed, under very general conditions, that singularities are unavoidable (in either the past or the future) in solutions of Einstein equations. A crucial role in the proof was played by the Raychaudhuri equation, derived more than a decade earlier, which demonstrated the focusing effect of gravity on matter which made the formation of singularities inevitable. The use of a local energy condition capturing the positivity of matter energy density showed that the essentially attractive nature of gravitation was ultimately what was responsible. The generality of the Hawking–Penrose result helped to not only settle the controversy on singularities, but also highlighted the power of the new techniques of global analysis that were brought to bear. These continue to play an influential role in classical general relativity and the textbook by Hawking and Ellis which approached the subject from this point of view is now a classic.

Classical properties of black holes

Given the generic nature of black holes and since tools were available to address their general behaviour, Hawking next turned his attention to them. The focus, however, shifted from the singularity to the event horizon. The event horizon is one of the most enigmatic and perhaps (at least, in the popular imagination) defining feature of a black hole. It is the region of space–time which typically cloaks the black hole singularity and is entirely shielded from an external observer. This is because even light rays are subject to the strongly focusing gravitational field within the event horizon and cannot escape outside. By bringing his powerful techniques to bear on the nature of the event horizon, Hawking was able to prove a number of results, striking in their generality. He could show that in four space–time dimensions, the two-dimensional surface which defines the event horizon at any given slice of time always has the topology of a sphere. He was further able to show that the area of this surface, no matter how complicated, must always increase (with time) if the matter obeyed the positivity of energy conditions mentioned above. This is what is often referred to as the area theorem. As we will see, this will play a central role in the developments to follow. Incidentally, Hawking also has a paper from that time in which he uses this theorem to put an upper limit on the efficiency of conversion of mass into gravitational radiation. Thus, when two nonrotating black holes collide, the efficiency is $(1 - \frac{1}{\sqrt{2}})$ or about 30%. In the light of the recently measured collision of black holes by the LIGO instrument, this is no longer such an abstract theoretical calculation (the observed efficiency was only about 5%)!

He also made an important contribution to the so called 'no hair theorem', building on earlier work of Werner Israel and Brandon Carter. This aimed to show that a black hole (in four-dimensional space–time) is completely characterized by its mass, charge and angular momentum (and not by more detailed characteristics of the kind of matter that went into forming it, for instance). Hawking's result here on axisymmetric solutions being given by the Kerr metric helped, together with later work by David Robinson, to firm up this statement.

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However, it was the area theorem which led Hawking, in work with Jim Bardeen and Carter, to further formulate the 'four laws of black hole mechanics' in analogy with the four laws of thermodynamics. The area theorem was the analogue, in this work, of the second law of thermodynamics, whereby entropy monotonically increases. Nevertheless, there was also a first law which in analogy with the thermodynamic law $\Delta E = T\Delta S$ (in its simplest form without additional potentials and work terms) reads as

$$\Delta M = \kappa \Delta A. \tag{1}$$

Here, M is the mass of the black hole and A is the horizon area.

Here the mass of the black hole played the role of thermodynamic energy, while the surface gravity κ (measuring the acceleration due to gravity at the horizon of the black hole) played the role of temperature T (in addition to the area being like the entropy, as observed earlier. There is a straightforward generalization to include additional work terms.). Moreover, κ was constant over the entire horizon and this was like in the zeroth law of thermodynamics, where temperature is a constant at equilibrium. Finally, there was an analogue of the third law in that it is apparently impossible to reduce κ to zero for a black hole through a finite sequence of processes. However, in their paper Hawking and collaborators stressed that this was only an analogy and that the actual temperature of a black hole was zero since it could absorb radiation but not emit anything.

Quantum properties of black holes

Jakob Bekenstein, on the other hand, took seriously the observation that black holes can apparently violate the second law of thermodynamics, since one can throw a cup of hot tea into the black hole and its entropy disappears from the rest of the universe, while the black hole being a unique object (the 'no hair theorem') cannot carry any entropy (either before or after the cup of tea was thrown into it). Taking inspiration from the Hawking area theorem, Bekenstein proposed that black holes do have a thermodynamic entropy proportional to the area. He proposed a generalized second law of thermodynamics in which the total entropy, namely the usual thermodynamic entropy external to black holes together with the entropy assigned to them, is always non-decreasing. However, Bekenstein did not have any reliable approach to fix the constant of proportionality to the area.

Taking inspiration from the Hawking area theorem, Bekenstein proposed that black holes do have a thermodynamic entropy proportional to the area.

Bekenstein's proposal was strenuously opposed by Hawking, since assigning an entropy meant black holes could also have a temperature and this was classically impossible as they could not emit radiation but only absorb it. During a Moscow visit in 1973, Hawking was influenced by the Soviet astrophysicists, Ya. Zeldovich and Alexei Starobinsky, who had described a classical phenomenon called superradiance from rotating black holes, and heuristically argued from the uncertainty principle for a similar quantum phenomenon. He attempted to rigorously incorporate quantum effects in the background of a rotating black hole. To his surprise he found a nontrivial spectrum of radiation even for a non-rotating (Schwarzschild) black hole. Moreover, the spectrum was exactly thermal (with a Planckian distribution of the frequencies) with a temperature – the Hawking temperature

$$T_H = \frac{\hbar c^3}{8\pi G_{\rm N} M k_{\rm B}}. \tag{2}$$

Here M is the mass of the black hole and the rest are fundamental constants such as the speed of light (c), Planck's constant ($\hbar$), Boltzmann's constant ($k_{\rm B}$) and Newton's constant of gravitation ($G_{\rm N}$). This formula for temperature was proportional to $\kappa(\propto \frac{1}{G_{\rm N}M})$, as foreshadowed by the laws of black hole mechanics, but fixed the constant of proportionality in terms of the Planck's constant. Thus, it demonstrates the intrinsically quantum nature of the phenomenon.

This immediately led, through the second law of black hole mechanics, to the constant of proportionality in the entropy formula of Bekenstein to be fixed – to be what is now called the Bekenstein–Hawking formula

$$S_{\rm BH} = k_{\rm B}\frac{Ac^3}{4G_{\rm N}\hbar}. \tag{3}$$

Thus Hawking showed that Bekenstein's proposal did make sense if quantum effects were taken into account. Classically, a black hole appears to be featureless and black, but it actually has a quantum mechanical entropy and a resultant blackbody spectrum of radiation. This underscores the centrality of quantum mechanics in deciphering the nature of black holes. Hawking's calculation opened a portal onto the quantum behaviour of gravity. We flesh out the significance and further developments of this crucial insight in the following section since it also played an important role in the evolution of Hawking's thinking.

Hawking realized that the perfectly thermal nature of black-hole radiation also created further tension in the ability to have a consistent quantum description of black holes. His observation was based on the fact that in quantum mechanics a state with a thermal density of radiation is a mixed state (or density matrix) as opposed to a pure state.

Shortly thereafter, Hawking realized that the perfectly thermal nature of black-hole radiation also created further tension in the ability to have a consistent quantum description of black holes. His observation was based on the fact that in quantum mechanics a state with a thermal density of radiation is a mixed state (or density matrix) as opposed to a pure state. However, the unitary time evolution of quantum mechanics (which is central to ensuring that the sum of all quantum probabilities add up to one) prevents pure states from evolving into density matrices. There arises then a paradox of how a black hole, which can be formed from the collapse of matter prepared in a pure state, can evolve into a thermally radiating object. In fact, eventually a black hole can completely evaporate leaving only the radiation behind. This puzzle is called the 'information paradox' and continues to be actively debated to the present day.

Quantum effects in cosmological space–times

Hawking, together with Gary Gibbons, realized in 1977 that certain cosmological space–times which have an exponentially accelerated expansion (known as de Sitter (dS) space–times) also exhibit features similar to the thermodynamics of black holes. The important similarity to the black hole case is the presence of an event horizon, now associated to a given observer. An observer in a dS space–time is only able to see a part of it even if she waits infinitely long, since the enormous acceleration takes regions of space–time out of causal contact with her. What Gibbons and Hawking realized was that such a cosmological event horizon can be assigned an effective Hawking temperature (directly proportional to the surface gravity κ and $\hbar$ as before) as well as an entropy proportional to the area of the two-dimensional surface (with the same constant of proportionality as in the black hole case). This area is inversely proportional the value of the cosmological constant parameter Λ. This cosmological entropy can be viewed as a measure of the ignorance of the observer to the degrees of freedom beyond her horizon.

When these ideas were put forward, dS space–time was more of a historical toy example of a cosmological space–time. It is rather remarkable that 40 years later, dS space–time is central to modern cosmology. With the discovery of a dark energy component and current-day acceleration, the universe is expected to approach dS space–time in the future as galaxies dilute away in the expansion. Moreover, the initial phase of the universe is believed to have had a period of exponential expansion known as inflation, whose signals have been measured in the tiny anisotropies of the cosmic microwave background radiation that bathes us all. Thus there is good reason to believe that the very early universe was also described by a dS space–time.

Thus when inflation was proposed in the early 1980s, Hawking was one of the first (together with Vyatcheslav Mukhanov and others) to realize that quantum fluctuations in dS space–time could be important. He realized that the scalar field which was believed to drive the inflationary expansion could give rise to quantum fluctuations that would give the right level of inhomogeneity to be the origin of all the large-scale structures we observe today in the clustering of galaxies.

Towards a quantum understanding of gravity

The problem of addressing the quantum fluctuations of the gravitational field, i.e. space–time itself, is a notoriously difficult one, as we briefly explain in the next section. Hawking tried to develop his own approach to this question in full realization that it was not complete or perhaps even fully consistent. The ideas proposed by him and his collaborators have nevertheless been influential. In some ways, Hawking was guided by the, then recent, successful application of non-perturbative techniques to studying quantum field theories, like non-Abelian theories (which are at the base of the standard model that describes all the forces of na-

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ture other than gravity). This was based on the path integral or Feynman approach to quantum theory. Here one sums over all possible configurations ('paths'), each weighted by a phase factor $e^{i\frac{S}{\hbar}}$ where S is the so-called action of the configuration and $\hbar$ is Planck's constant. Many of the nonperturbative effects in non-Abelian theories were uncovered by considering a so called 'Euclidean' theory in which time is taken to be imaginary and therefore the above weighting factor actually becomes $e^{\frac{-S}{\hbar}}$.

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While their proposal was very original, the parallels between non-Abelian theory and gravity do not quite hold at the path integral level. Unlike non-Abelian theories, the action for gravitational configurations can take arbitrarily large negative values. This is associated with the overall size factor of the metric. It makes the sum over the configurations much less well-defined in gravity. Nevertheless the no-boundary proposal and similar ideas in quantum cosmology may have a role to play as a semi-classical approximation to a more fundamental description.

The Puzzles of Black Holes and Quantum Gravity

How has Hawking's work shaped the development of physics in the last several decades? We concentrate on some of the major themes. In particular, Hawking's work on the quantum aspects of black holes gave a quantitative target, for physicists trying to understand the quantum nature of gravity, to come up with a complete and mathematically consistent theory which can microscopically account for the Bekenstein–Hawking entropy of black holes. This challenge had a profound impact on the development of string theory, a framework of theoretical physics that has many of the ingredients of being a quantum theory of gravity, and which has achieved a measure of success towards understanding the questions raised by Hawking's work.

Quantum theory and Einstein gravity

We have already discussed the inevitability of focusing singularities that indicate a breakdown of general relativity. In particular, the past singularity raises fundamental questions about the notion of space–time in the initial instants of the universe. How would these singularities be resolved in a quantum theory? This is a question which we are still far from definitively answering. We have also discussed his work on the relativistic quantum field theory in the presence of a black hole, which led to the notion of thermo-dynamic entropy for black holes and the 'information paradox'. In deriving both these results the gravitational field (i.e. the metric of space–time) was treated classically. However, a complete theory would also require a consistent quantum treatment of gravity as well. In fact, there can be no statistical mechanical accounting of the black-hole entropy without such a microscopic quantum description of gravity.

The programme to quantize gravity using the Einstein–Hilbert action as a starting point began in the early 1960s (see ref. 2 and references therein). Just as a photon is a quantum of the electromagnetic field, the graviton, a massless spintwo particle, was viewed as a quantum of the gravitational field. The strength of the emission and absorption of gravitons is characterized by the dimensionless ratio E/E_{pl}, where E is the typical energy of the gravitons and $E_{pl} = (\hbar c^5/G_N)^{\frac{1}{2}} \sim 10^{19}$ GeV. This indicates that at energies $E \sim E_{pl}$ (Planck energy) or equivalently time intervals $\delta t_{pl} \sim 10^{48}$ sec, quantum fluctuations of space–time are so large that the theory breaks down. Unlike the case of electromagnetism where quantum mechanics regulates the singular behaviour of the

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$1/r$ Coulomb potential, in gravity this does not happen. Furthermore, such a quantum field theoretic approach to gravity could not give the unusual area dependence (as opposed to an extensive volume dependence) of the black hole entropy on its size (as measured by the extent of the event horizon).

Thus, a simple-minded quantization of matter and gravity runs into seemingly insurmountable problems. The question then arises whether there is a more fundamental theory that is, (1) valid at $E \sim E_{pl}$ and whose low energy ($E/E_{pl} \ll 1$) limit is Einstein's theory, and (2) rich enough to account for all the microstates that can explain black hole entropy and Hawking radiation consistent with the principles of quantum statistical mechanics. The answer to both these questions is yes, within the framework of string theory. Whether this framework of string theory is indeed what nature chooses is something that remains to be established. But the very fact that there is a consistent framework which is able to address both the above questions, makes it compelling to consider and shed considerable light on Hawking's results. Here, we will not describe the string theory answer to the first question, but concentrate on the second question [3].

String theory microstates, black hole entropy and Hawking radiation

In order to see how string theory addresses this question of black hole entropy, we turn to an analogy to help explain the basic point. Consider a fluid like water which is described by the dissipative Navier–Stokes equations. This description is essentially in terms of a smoothly evolving velocity field of the fluid. It is one of the great discoveries of science (from the 20th century) that underlying this continuum (field) description of the fluid are microscopic interacting molecules obeying the laws of quantum mechanics, and that the thermodynamic entropy of the system can, in principle, be calculated using Boltzmann's formula $S = k_{\mathrm{B}} \log \Omega$, where Ω is the number of microstates. We need the quantum mechanics of atoms and molecules to properly account for the thermodynamics of water. Returning to black holes we could ask: Are there quantum microstates in string theory which would account for the Bekenstein–Hawking entropy upon using Boltzmann's formula?

String theory microstates: In 1995, Joseph Polchinski (building on earlier work by Jin Dai, Rob Leigh and Joe Polchinski, as well as Petr Horava) gave a precise understanding of a class of nontrivial classical solutions, now called D(irichlet) p-branes, in superstring theory. These are special types of domain walls, carrying generalized electric/ magnetic charges, and of spatial dimension between 0 (points) and 9, labelled by p. These domain walls are the endpoints of open strings, with their oscillations and interactions described by the emission and absorption of open strings. At low energies these are described by non-Abelian gauge fields (of the same variety that appears in the standard model of elementary particles). At the same time, they are massive and source gravity. In summary, D-branes are heavy, gravitationally interacting objects whose dynamics can be described by non-Abelian gauge fields. This crucial observation underlies the microscopic accounting of black hole entropy in string theory and the more general Anti-de Sitter/Conformal Field Theory (AdS/CFT) correspondence outlined in the next section.

Bekenstein–Hawking entropy = Boltzmann entropy: This was the basis for the landmark paper in 1996 of Andrew Strominger and Cumrun Vafa. They considered a particular (extremal) black hole solution in type-IIB string theory and showed that it can be viewed as a bound state of D1 and D5 branes. They demonstrated that the Boltzmann entropy of this system is identical to the Bekenstein–Hawking entropy, including the precise proportionality factor that Hawking had derived. This demonstrated for the first time that black holes are composed of micro-states that are not contained in Einstein's theory of general relativity. The latter appears as a mean field description of the physics of the microstates in terms of a metric field, much as in the Navier–Stokes analogy.

Hawking radiation: Extremal black holes do not Hawking radiate. However, the Hawking radiation of a 'near extremal' black hole was microscopically modelled in terms of a slightly excited D1–D5 system coupled to gravitons by Avinash Dhar, Gautam

Mandal and Spenta Wadia, as also Sumit Das and Samir Mathur, Juan Maldacena and Andy Strominger. After some effort, the statistical formulas for Hawking radiation rates agree with those derived from general relativity, including details such as the grey body factor. Hence in a toy model of black holes in superstring theory, the information paradox presented in Hawking's 1975 paper could be analysed in all detail in a technically tractable way. It is important to emphasize that the above result could be derived in the favourable circumstance where the black hole is a bound state of D-branes. For example, the discussion does not apply to a Schwarzschild black hole. At the same time, it should be stressed that geometrically these black holes are not much different from the charged cousins of Schwarzschild black holes. Also, these are not isolated examples and there is a plethora of such solutions for which the Strominger–Vafa calculation has been generalized with amazing success. Furthermore, one can systematically derive corrections to Hawking's result, as shown by Robert Wald [4], which have also been reproduced by the microstate analysis. It is important to note that in these examples the 'information puzzle' can be directly addressed [5].

Quantum gravity as a quantum field theory: The AdS/CFT correspondence

A much more comprehensive view of the microstate counting of black hole entropy was enabled by the insight of the AdS/CFT correspondence of Maldacena in 1997. This relates all quantum gravitational phenomena in asymptotically Anti de Sitter space–times (with the opposite sign of the cosmological constant from the dS space–times mentioned earlier) holographically through a unitary non-Abelian theory on the boundary of the space–time. Thus space–time emerges due to the strongly coupled and highly entangled quantum field theory on the boundary – a remarkable new conceptual paradigm in physics. In particular, it indicates that the 'mean field' description of many (all?) strongly coupled quantum field theories is the gravitational field that lives in one higher dimension. This correspondence in now 20 years old and is still a beacon in our search for the complete theory of quantum gravity. It gives a concrete case study of a nonperturbative theory of quantum gravity in a large class of space–times.

In this concrete setting, phenomena like black hole evaporation obey the rules of quantum mechanics. Thus, in principle, the information loss puzzle for black holes in AdS space–times has a resolution. This is what led Hawking in 2004 to concede that he was wrong regarding the breakdown of quantum mechanics in the presence of a black hole. However, the question remains to pinpoint how exactly Hawking's arguments, made within the framework of the mean field theory of Einstein equations, break down. Probing deeper has led to investigations of quantum entanglement and non-locality in quantum gravity, and the correspondence of degrees of freedom inside and outside the horizon of a black hole [3, 6].

Hawking's work and non-gravitational physics

The AdS/CFT correspondence displays the power of the string theory framework in unifying diverse physical phenomena. We list in the following a few remarkable formulas of strongly coupled quantum systems that follow from this correspondence. In all of them Hawking's results play a central role and powerfully demonstrate how far-reaching and profound their impact has been – even on physics which has apparently little to do with gravity.

• A universal form for the ratio of viscosity to entropy density of a strongly interacting relativistic fluid is obtained by perturbing a static black hole by an in-falling wave. In the boundary field theory, this generalizes thermodynamics to dissipative hydrodynamics, and AdS/CFT relates the viscosity to the absorption cross-section (at zero frequency) of the wave incident on the black hole

$$\frac{\eta}{s} = \frac{\sigma}{16\pi G_N s} = \frac{A}{16\pi G_N s} = \frac{\hbar}{4\pi k_B} \tag{4}$$

In the above we have used the Bekenstein– Hawking entropy formula. This has proved influential in understanding the physics of the strongly interacting quark–gluon plasma [7]. These ideas led to a precise derivation of relativistic hydrodynamics and transport coefficients from the Einstein equations in AdS, and also to the discovery of new terms in superfluidity. Another application was to use the area theorems to show the positivity of the entropy current in fluid dynamics [8].

• A formula for quantum entanglement entropy of a region A in a strongly coupled field theory was proposed by Shinsei Ryu and Tadashi Takayanagi

$$S_A = \text{Area}(\gamma_A)/4\hbar G_N, \tag{5}$$

where Area (γ_A) is the minimal area surface (co-dimension two) γ_A in AdS space–time, whose boundary is the same as that of the region A. Even though it is superficially of the Bekenstein–Hawking form, there needs to be no horizon and or even a black hole. It exhibits a deep connection between quantum information theory and Hawking's formula [9].

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• Black holes scramble information most efficiently. In the quantum field theory, this corresponds to the 'butterfly effect' that describes how a small disturbance in the far past spreads through the system characterized by an exponential growth $e^{\lambda t}$. The exponent λ is the analogue of the Lyapunov exponent for many-body systems and it is most easily calculated in the gravity theory to be

$$\lambda = \kappa, \tag{6}$$

where $\kappa = 2\pi k_B T$ is the surface gravity and T is the temperature of the black hole. This inspired the proof that $\kappa = 2\pi k_B T$ is the maximum value ('chaos bound') of such an exponent in a unitary quantum system [10]. An example of any quantum mechanical system that has a maximum value of the exponent λ is the Sachdev–Ye–Kitaev model of real fermions with disorder. This shows how the physics of black holes implies certain universal characteristics for down-to-earth physical systems!

Stephen Hawking celebrating his 59th birthday during his visit to India. Photo credit: TIFR Archives.

Hawking's Visit to India

Hawking visited India on the occasion of the Strings 2001 meeting that was held at the Mumbai campus of TIFR. It was the first meeting of this series to be held outside of North America and Western Europe, and it was an international recognition of the contribution to string theory from India. He participated in this meeting as an invited speaker together with other eminent scientists like David Gross and Edward Witten.

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Hawking had a zest for life. During the conference banquet we celebrated his 59th birthday and he danced with his wife – swirling his chair around back and forth. A vivid memory of his visit is the warmth and care he showed towards the many people from all walks of life who met him. Children from TIFR's housing colony had a meeting with him, which was so inspiring for them.

Hawking's visit to India was quite a nontrivial feat to arrange given his special condition. It required the active support of many members of Indian civic society. S. D. Shibulal (co-founder of Infosys Technologies and an alumnus of TIFR), stepped in on behalf of the Sarojini Damodaran Foundation to bear the considerable expenses involved in bringing Hawking to India. The Mahindras provided a custom designed van which enabled Hawking's local transport. It is a measure of the universal regard, with which Hawking was held, that all this support materialized, without which the visit would not have happened.

Another important outcome of Hawking's visit to India was that science and its mysteries were in the public eye for a week or more. His visit also helped highlight the string theory contribution from India, in India. His presence in the country was quite a sensation and the media was fully focused on him, even joining him for a walk along Marine Drive. R. K. Laxman's cartoon of Hawking appeared in the Times of India; Hawking also gave a public lecture at the Shanmukhananda hall in Mumbai and the huge hall was filled to capacity. He visited Delhi to deliver the Albert Einstein Memorial Lecture and called on the then President of India, K. R. Narayanan at Rashtrapati Bhavan.

Hawking and Science Popularization

Hawking was indeed a great global ambassador for fundamental science. Through his book, *The Brief History of Time* and subsequent popular science works and public engagements, he was able to create a worldwide connect with the cosmic questions that physicists wrestle with. His book sold more than 10 million copies and was translated into over 40 languages. He was easily the most well-known living scientist for the general public for more than two decades. His life story, of a brilliant mind trapped in a failing body and yet able to transcend these limitations to do creative work of the highest order on some of the most fundamental questions asked by mankind, was genuinely inspirational. He followed up the success of his bestseller with a number of other books which updated and elaborated on *The Brief History of Time*. A very engaging series of books aimed at sparking the interest of children in science was coauthored with his daughter Lucy Hawking. In addition, the large number of documentaries on his science and work as well as the Hollywood film 'The Theory of Everything' made Hawking the universally recognizable face of theoretical physics. It is clear that his story will continue to inspire many future generations to dedicate their lives to the quest to answer the mysteries of the universe.

Suggested Reading

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