This is the tenth year of ICTS—TIFR since it came into existence on August 2, 2007. ICTS has now grown to a team of fifteen faculty members studying various areas in the theoretical sciences. Over 150 programs and discussion meetings have been held.

A discussion meeting, *ICTS at Ten*, was held to celebrate the occasion. It was an opportunity to reflect on the journey thus far, and to go ahead with renewed energy into our second decade, through a small celebratory scientific gathering. The theme of the meeting was ‘Celebrating the Unity of Science’.

Over the course of this meeting, speakers from around the world gave broad perspective talks across different themes in the theoretical sciences: Astrophysics and Cosmology, String theory and Quantum Gravity, Mathematics, Theoretical Computer Science, Condensed Matter and Statistical Physics, and Physical Biology.

These areas reflect ICTS’ present profile as well as the directions it would grow into in the coming years. The talks, by a galaxy of distinguished researchers, shed light on some exciting frontier questions in these areas.

The talks were held at the Chandrasekhar auditorium of the ICTS Campus located in north Bangalore and were attended by over 200 participants.
The Usefulness of Useless Knowledge

On the afternoon of Sunday, the 7th of January, Robbert Dijkgraaf, IAS, Princeton delivered the public lecture on ‘The Usefulness of Useless Knowledge’ emphasizing the role of fundamental research, which seems useless at times but often later turns out to play a significant role in technologies serving mankind.

The lecture was followed by a panel discussion on:
• Global spread of science in the 21st century – what are its dynamics and how is it going to happen?
• Role of three entities in society in funding scientific research – funding coming from Govt, individual philanthropy and corporate sectors and how can they be most effective in doing so.
• Fundamental science in India – what role it has played in India and what role should it play. As well as the role of Science education.

The panel was moderated by Rajesh Gopakumar and the panelists were introduced by Spenta Varia (Princeton University), Jennifer Chayes (Microsoft Research, New England), David Gross (KITP, Santa Barbara), Narayana Murthy (Co-founder, Infosys Technologies) and K. VijayRaghavan (NCBS—TIFR & Secretary, DBT, Govt. of India).

Exploring the Universe with Gravitational Waves: From the Big Bang to Black Holes

On the 11th of January, ICTS witnessed a gathering of over 1500 students and members of civic society who had come to attend the first ICTS Vishveshwara Lecture (the public lecture series through which ICTS celebrates the life and work of C. V. Vishveshwara) delivered by Kip S. Thorne, Feynman Professor of Theoretical Physics at Caltech and 2017 Nobel Laureate in Physics on ‘Exploring the Universe with Gravitational Waves: From the Big Bang to Black Holes’.

Thorne talked about the two types of waves that can propagate across the universe: Electromagnetic waves and gravitational waves. Galileo initiated electromagnetic astronomy 400 years ago by pointing a telescope at the sky and discovering the moons of Jupiter. LIGO recently initiated gravitational astronomy by observing gravitational waves from colliding black holes. Thorne described this discovery, the 50 year effort that led to it, and the rich explorations that lie ahead.

The Science of the Man from the 9 Dimensions

On 14th January, there was a talk by Hirosi Ooguri, Fred Kavli Professor of Theoretical Physics and Mathematics, Director of Walter Burke Institute for Theoretical Physics, Caltech on ‘The science of the man from 9 dimensions’, followed by a 3D dome movie screening of ‘The Man from the 9 Dimensions’. This was a special premiere of this spectacular movie in India at the Sky Theatre, JN Planetarium, Bangalore. The Chief Guest for this special event was Sudha Murty from the Infosys Foundation.
Quantum Entanglement and the Geometry of Spacetime

Matthew Headrick

Almost since quantum mechanics and general relativity were discovered around a hundred years ago, theoretical physicists have been trying to unify them. Step by step, this struggle has borne fruit, often in surprising ways and with unexpected implications. Forty years ago, string theory, the first genuine theory of quantum gravity, was found.

Twenty years ago, a remarkable discovery came out of string theory: quantum mechanics and general relativity are not separate theories, but, rather, in some sense, two sides of the same coin. This connection between quantum mechanics and general relativity goes by the name “holography.” Ten years ago, theorists studying holography discovered that there is a direct and beautiful relation between entanglement, a central concept in quantum mechanics, and spacetime geometry, a central concept in general relativity. In this article, I will attempt to convey a bit of the story of holographic entanglement, and why I call it “holography.”

I will start by exploring a few essential aspects of quantum mechanics and general relativity. Quantum mechanics (QM), which is necessary for an accurate description of systems on an atomic and subatomic level, radically alters our notions of the state of a physical system. While a particle in classical mechanics has, at any instant of time, both a definite position and a definite momentum, it is uncertain to what extent these two properties are actualized. The principle in QM that can have neither. This uncertainty leads to the strange phenomenon of entanglement.

Entanglement is a kind of correlation between different parts of a quantum system; for example, in the positions of different particles. In classical mechanics, correlations between different parts of a system occur only in a statistical sense, when we are ignorant of the true state of the system. Consider, for example, a distribution of possible positions of a pair of particles. If in that distribution the particles are always close to each other, then their positions are statistically correlated. On the other hand, in any actual state, every physical variable has a definite value, including those specifying the states of the parts (for example, the position of each individual particle); since there is no uncertainty, there is no room for correlations. In QM, however, the fact that even in a fixed state physical variables do not take on definite values opens the door to correlations that are intrinsic to the state, rather than reflecting any statistical description or lack of knowledge on our part. Such correlations are called entanglement.

Entanglement is the key to understanding the geometry of space. In classical mechanics, you could specify all the possible positions and momenta of particles in spacetime, take on definite values. The problem of finding minimal surfaces is called the Plateaux problem. Ryu and Takayanagi thus asserted that, in holographic systems, quantifying entanglement is similar to the Plateaux problem; for example, a soap bubble stretched across a wire would arrange itself into a minimal surface. The mathematical problem of finding minimal surfaces is called the Plateaux problem. Ryu and Takayanagi thus asserted that, in holographic systems, quantifying entanglement is similar to the Plateaux problem; for example, a soap bubble stretched across a wire would arrange itself into a minimal surface. The mathematical problem of finding minimal surfaces is called the Plateaux problem. Ryu and Takayanagi thus asserted that, in holographic systems, quantifying entanglement is similar to the Plateaux problem; for example, a soap bubble stretched across a wire would arrange itself into a minimal surface.

In 1997, building on investigations of black holes in string theory, Juan Maldacena discovered a very surprising direct connection between QM and GR. He showed that certain quantum-mechanical theories are—in a very peculiar sense—also governed by GR. The QM theories in question are similar to the one that governs the strong nuclear force which binds quarks inside atomic nuclei (called quantum chromodynamics). In these theories, space and time have a fixed geometry and there is no force of gravity. Yet Maldacena showed that they admit a radically different kind of description, which is classical, has a dynamic spacetime geometry, and includes the force of gravity.

And there is another important difference: the GR description has an infinite number of dimensions compared to the QM description. For example, in certain cases the QM system lives in three or more—dimensional spacetime, while the GR description has a four—dimensional spacetime. In others, the QM has two dimensions (lives on a plane), while the GR, like our world, has three.

Such a relationship is analogous to a hologram, in which a pattern on a piece of two—dimensional film gives rise to the appearance of a three—dimensional object. For this reason, the correspondence between QM and GR discovered by Maldacena is called “holographic.”

Before proceeding, we should emphasize one point. It may at first sight seem shocking that a quantum system can ever appear to be classical. In fact, this is the least surprising aspect of holography. After all, any macroscopic object, such as a tennis ball, being composed of electrons and other particles, is strictly speaking governed by GR, yet in describing its motion quantum effects get washed out and classical mechanics is perfectly adequate. The systems considered by Maldacena similarly contain a very large number of physical degrees of freedom; in this case, a very large number of fields. Such systems had already been studied by theorists for decades, and the fact that the collective behavior of these fields is well described by classical mechanics was already anticipated in the 1970s by Gerard ’t Hooft. Holography is the formal and useful description of this collective behavior which we now call “holography.”

In the type of quantum theory considered by Maldacena, not only are there a large number of physical degrees of freedom, but they interact very strongly with each other. These interactions are very difficult to study by traditional theoretical methods. However, their equivalence to GR makes them relatively tractable, because classical theories are always much easier to deal with than quantum ones. Holography has therefore proven incredibly useful for modelling a wide variety of strongly—interacting quantum systems, from cold atoms to extreme temperatures to extreme superconductors. Conversely, holography also provides a new perspective on GR and gravity. While the GR description of the universe considered in this article is exactly the same as the one that governs our universe (in particular, the cosmological constant is negative, in contrast to the observed positive cosmological constant, or “dark energy”), it is natural to speculate that, even for some not yet understood, the apparently smooth, classical spacetime is really just a representation of a collection of a very large number of strongly interacting quantum—mechanical degrees of freedom; to speculate, in other words, that space, time, and gravity are emergent phenomena.

We emphasized above that entanglement is one of the thorniest questions at the intersection of QM and GR, and attempted to build up GR from this starting point. A notable success has been the derivation of the Einstein equation, the fundamental equation governing GR, from the GR—Takayanagi formula. Since 2006, the study of holographic entanglement has multiplied in many directions. Since Ryu and Takayanagi proposed a formula for the degree of entanglement between two parts of a holographic quantum system, quantified by a certain entropy. According to their formula, this “entanglement entropy” is given by the area of a certain minimal surface in the spatial representation of the GR side. A minimal surface is one with the smallest possible area subject to some boundary condition; for example, a soap bubble stretched across a wire would arrange itself into a minimal surface. The mathematical problem of finding minimal surfaces is called the Plateaux problem. Ryu and Takayanagi thus asserted that, in holographic systems, quantifying entanglement translates into a Plateaux problem.

The area here is measured in Planck units, the fundamental units of quantum gravity. In relating the entanglement entropy to the area, Ryu and Takayanagi inspired by the relation discovered by Jacob Bekenstein and Stephen Hawking in the 1970s, giving the entropy of a black hole by the area of its event horizon in Planck units. (See the figure for an illustration of the Ryu–Takayanagi formula.)

Since 2005, the study of holographic entanglement and its generalizations has been one of the most exciting developments in theoretical physics in this century so far. What other new concepts are waiting to be discovered, and what other unexpected connections? We can’t wait to find out.

Matthew Headrick is a theoretical physicist and a faculty member at Brandeis University, USA.
GRAVITY’S FATAL ATTRACTION
B. S. THAYAPARAKASH

The 2017 Nobel Prize in physics was awarded to Kip Thorne, Barry Barish and Rainer Weiss for decisive contributions to the LIGO detector and the observation of gravitational waves. What is LIGO, what are gravitational waves and why was a Nobel Prize given for their observation? These are the questions I wish to pursue in this article and tell you how gravity’s fatal attraction leads to cosmic ‘cannibalism’.

A Brief History of Gravity: Tycho Brahe to Urbain Le Verrier
Gravity is the oldest force known to us. It took us about 2400 years to realize that gravity’s fatal attraction leads to predictable paths. One of Brahe’s assistants was Johannes Kepler, whose careful analysis of the data revealed the three laws of planetary motion that we still teach today: (1) planets follow elliptical paths with the Sun at their focus, (2) a line connecting a planet and the Sun sweeps out equal areas in equal times, and (3) the square of the period of a planet is proportional to the cube of its semi-major axis. These laws paved the way for Newton to discover his laws of gravitation.

Enter Einstein
In the end, Einstein was able to reconcile precession of perihelion of Mercury in 1915 with his new theory of gravity, which he called the general theory of relativity. In this theory, all forms of matter and energy can produce gravity including gravitational self-energy. This nonlinearity of gravity, Einstein showed, could fully explain the orbital motion of Mercury.

Einstein’s theory has had deep impact on our understanding, not just of gravity but the very structure of space and time. According to Newton, space is rigid, time is absolute, and there are no free will and physical interactions that take place in the immeasurable arena of space and time. It didn’t affect in anyway. In Einstein’s special relativity, space and time are unified and could transform into each other. In particular, observers who are in relative motion assign different time and length intervals between the same physical events. Although space and time are unified, the spacetime itself is a rigid structure in special relativity.

Upon unifying special relativity with gravity, Einstein found that the structure of spacetime, in particular how it is curved, was determined by mass and energy. John Wheeler captured the essence of Einstein’s general relativity by famously saying that matter tells spacetime how to curve and curved spacetime tells matter how to move. What is this curvature of space and time?

Warping and Dynamic Spacetime
Warping of space causes proper distances1 between test masses to change, e.g. a pair of test masses appear to come closer together as they fall towards the center of the Earth. Curvature of time is to do with the rate at which clocks tick, e.g. clocks at the bottom of Eiffel Tower would tick slower relative to those at the top. Moreover, changes in the distribution of mass and energy, in particular accelerated masses, would cause change in spacetime to change as well. The change in warping, according to Einstein, propagates from the source at the speed of light and this will be seen as changing cause in proper distance between free test masses. These propagating ripples in the curvature of spacetime are called gravitational waves and the amplitude of the waves is measured by the Einstein-Jordan parameter $\Delta L/L$.

Soon after proposing his new theory of gravity, Einstein showed that his equations of general relativity naturally gave rise to the phenomenon of gravitational radiation. However, not everyone was convinced of their physical reality or how one might detect them. This was because the formulation of a relativistic theory of gravity required mathematical objects (i.e., the metric tensor) endowed with more degrees of freedom than were physically necessary so that the theory could be used for a metric in an inertial or non-inertial reference frame. General relativistic equations are valid for all observers but there is no unique way to pick one to has to deal with many coordinate systems and recognizing the true physical degrees of freedom took decades after the theory was formulated.

Theoretical work by Hermann Bondi, Felix Pirani and Igor Robinson in the late 1950s resolved conceptual difficulties that plagued theorists for decades, by showing that wave equations of free mass in general relativity were not spurious but carried real physical content and linear and angular momentum from their sources to infinity. American physicist Joseph Weber was the first to appreciate their significance. He built bar detectors for observing gravitational waves from cosmic events. The sensitivity of his detectors was not good enough to observe radiation from even the most catastrophic events such as supernovae in our own galaxy.

Strongest Sources
In general relativity, the magnitude of curvature produced is proportional to mass and energy density. The constant proportionality is $G/c^4$, where $G$ is Newton’s constant of gravitation and $c$ is the speed of light. It has dimensions of $1/force$. This force is enormous: $10^{44} N$. It implies that even small disturbances in large systems can be so large that produces forces which can be expected the warp of spacetime to be perceivable. What sort of systems experience this force? As stated before, accelerated masses generate gravitational waves.

Therefore, let us consider a binary system of stars of total mass $M$, with mass $M_1$ and $M_2$. The centrifugal force experienced by the two stars is $F = M_1 v_1^2/r_1 = M_2 v_2^2/r_2$, where $r$ is the distance between the bodies. In the last of the quantities I have used Kepler’s second law $v_1^2 = GM_1/r_1$. We can rewrite the centrifugal force as $F = G M_1 M_2/ (r_1 r_2)$. Since $r_1 > r_2$, the centrifugal force is always smaller than $G M_1/ r_1$, coming closer to the Sun at $r_2$. To make it close I choose you would need to put together binary companions in a very tight orbit. But most astronomical binaries (planetary orbits, binaries of main sequence stars, binary white dwarfs etc.) would begin to touch each other before a can approach. However, in the case of a black hole and neutron star—binary stars, referred to as compact binaries, can get close to $10^{-7}$ for very tight orbits; it is only in such cases that gravitational waves produced are the largest ever possible, but they would remain in this phase for only a few minutes or seconds. But how would you put a binary in a tight orbit?

Binary black holes and neutron stars could form as a result of mergers of massive stars. Currently, regions of stars are very hot. They burn hydrogen, helium and other elements to produce high energy radiation at their core. The resulting radiation pressure holds stars from collapsing against their own gravity. A binary black hole or neutron star could form whenever massive stars exhaust their nuclear fuel and cannot hold out against their self—gravity any longer. But a compact binary that forms in this way is usually very wide and an extremely weak source of gravitational waves. However, this loss of radiation can make the two compact objects spiral in towards each other and after hundreds of minutes of orbital evolution their spins would reach the speed of light and they would merge together in a big burst of radiation for a short duration at the time of merger the luminosity in gravitational waves from a binary black hole, no matter how massive they are, exceeds the luminosity of the entire Universe in light. So, these sources are literally the most powerful sources in the Universe. For this reason, Kip Thorne argued, the final few minutes and seconds of binary black holes and neutron stars will be the most powerful sources of gravitational waves and could be detected by a sensitive detector built here on Earth, even if the merger occurs billions of light years from Earth. Other potential sources of gravitational waves include supernovae, rapidly spinning neutron stars, stochastic backgrounds produced in the early Universe etc. The question then was what sort of detectors would be sensitive enough to detect such sources.

Laser Interferometer Detectors
As gravitational waves propagate through space, they stretch and squash space in the same manner as the Sun and Moon cause tidal deformation of Earth. Consequently, the distance between a pair of free test masses would oscillate in harmony as gravitational waves pass by. As with tides, the bigger the separation of test masses, greater will be the extent of deformation caused by the waves. By positioning two or more detectors in such a way that the waves travel in different directions one can, in principle, detect gravitational radiation. However, even the most powerful events cause an observable effect of at most a few parts in 1000 of a second, and the only way one could detect its presence would be to put a binary in a tight orbit. Detecting such length changes is a formidable technical challenge.

Kip Thorne was among the first to realize that Michelson interferometer might be such a detector. He imagined two arm interferometer, that is a laser and a mirror suspended at the ends of the test arms as test masses. Weiss and Thorne were among key scientists who proposed to build the Laser Interferometer Gravitational-Wave Observatory (LIGO, for short). From the beginning, they realized that this will not be just a fundamental physics experiment to detect gravitational waves to prove their existence but an observatory that could help us understand how the physical universe works by using this new radiation to study the interior of stars.

The above was a simple way to extend astronomical observations from optical to infrared radiation, radio waves, x-rays, gamma—
Gravitational wave detectors can localize sources of incident gravitational waves. LIGO and Virgo have so far observed six binary black hole mergers. The characteristics of the observed systems are shown in Table 1 and their masses and waveforms in Fig. 4. It is immediately apparent that the Universe is awash with a spectrum of black hole masses. From the observed population of black holes, we can hope to one day learn how black hole binaries form and evolve. However, it is unclear that black hole effective spins (see Table 4) are clustered around a value of zero. The effective spin is the mass-weighted sum of the black hole spins projected in the direction of the orbital angular momentum. It is possible that the companion black hole spins are tilted randomly with respect to the orbital angular momentum, but this would not lead to a low value of effective spin for every observed system. It is also possible that black hole spin magnitudes are intrinsically very small but it is simply difficult to measure. In any case, it is clear that black holes have to get rid of their large angular momentum before they collapse. Finally, it is plausible that we are observing the merger of pristine black holes, in which case small intrinsic spins are natural. The observed population is still small and measurement errors are large and so we cannot make definitive conclusions yet about the formation mechanisms of these black holes.

Gravitational wave detectors can localize sources of incident gravitational waves. The left panel shows masses of binary companion and of the merger remnant. The right panel shows gravitational waveforms for the first four detections as observed by LIGO.
at billions of light years from Earth. Although gamma ray observatories like SWIFT, INTEGRAL and Fermi have detected sources of SGRBs, there has been no conclusive observation of the expected afterglow in other parts of the electromagnetic spectrum. No one knew for sure but simultaneous observation of gravitational waves (which would carry the telltale signature of the inspiral and merger of neutron stars), gamma-rays and other radiation could settle the matter.

August 17, 2017, just a little over a week before the LIGO and Virgo detectors were shut down on August 17, 2017, just a little over a week before the matter. Dubbed the LIGO and Virgo observatories recorded a short burst just two weeks before the merger that produced the gamma ray observatories like SWIFT, INTEGRAL and Fermi, a young neutron star that was born in the wake of the merger of two neutron stars.

Not everything is hunky and dory. Many puzzles remain for: a GRB that occurred so close, the intensity was far too weak, raising questions about the nature of the gamma-ray jet and the central engine that produced it. The aftermath of the merger should have produced a highly oblate, bar-like object that is not expected to be large but we do not know how long the bar-shaped remnant lasted or what it looked like. Heavy—massive neutron stars, before collapsing to a black hole, assuming a black hole did eventually form. More sensitive detectors are required to resolve these and other questions such as how stiff neutron stars are, their size compared to their mass and the composition of their cores.

First of all the gravitational—wave observatories


The basic physics of the binary black hole merger GW150914, B. P. Abbott et al. Annalen Phys. 529 (2014)

References

1 Proper distance between two bodies is the distance between them in a reference frame in which they are both at rest.

2 In comparison, Newton’s laws of mechanics are valid only in inertial frames, in non—inertial frames the fundamental physics of the binary black hole merger GW150914, B. P. Abbott et al. Annalen Phys. 529 (2014)

3 The chirp mass $M_c$ of a binary composed of masses $m_1$ and $m_2$ is $M_c = (m_1 m_2)^{3/5} (m_1 + m_2)^{-1/5}$. According to general relativity the rate at which the signal’s frequency increases depends predominantly on this combination of the component masses.

B.S. Sathyaprakash is an astrophysicist and a professor at Penn State University, USA & Cardiff University, Cardiff, UK. w

The Scientific Legacy of Stephen Hawking (1942–2018)

RAJESH GOPAKUMAR & SPENTA R. WADIA

Biographical Details

Stephen Hawking, born 8th January 1942, at Oxford in an academic family had an early aptitude and inclination towards science. He studied physics and chemistry at 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 Ph.D., hoping to study cosmology with Fred Hoyle but instead was assigned to Dennis Sciama. It was at this time that he was diagnosed with motor neurone disease, a degenerative motor neuron disorder.

Hawking’s life was marked by his determination to continue his work and to communicate his ideas. He was given 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 at the time of his thesis in 1966. He remained at Cambridge as a fellow of Gonville and Caius College for much of his research career, except for a stint as the Sherman Fairchild Distinguished Professor at Caltech from 1970 to 1975. He was elected at age 32 as a Fellow of the Royal Society of London and appointed in 1979 to the orbiter Lucasian Professorship of Mathematics (held by Newton, Darwin, 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 a voice synthesizer, he maintained a remarkably productive scientific career which continued with research publications almost till a few months before his demise on 14th March, 2018.

Below we first sketch the important scientific contributions by Hawking hoping to convey to a broad scientific audience the path—breaking nature of his discoveries. We also felt that it is 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.

The Major Scientific Contributions of Hawking

In a foreword in 1993, to a collection of his papers, Hawking writes “With hindsight, it is true to say that there had been a grand and promiscuous 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. I was very much trying to see the coherence of ideas as well as the 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 seventies, peaking with the remarkable discoveries of the mid—seventies that he is most celebrated for.

In this section, we trace the remarkable trajectory with breadth and depth. He begins with his fundamental work on singularities in the classical theory of general relativity in the sixties. This led to pioneering work on general properties of black holes, at first in the classical theory, but eventually incorporating quantum effects and raising the fundamental questions that have not been fully resolved to this day.

Realising 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 matter which made the formation of singularities an essential part of the solution of Einstein equations. A crucial role in solutions of Einstein equations. A crucial role in formulating the 'four laws of black hole mechanics' in analogy with the four laws of thermodynamics. The area theorem was the analogue of the first law of thermodynamics in this context. The second law of black hole mechanics was nothing but the area theorem, but it was also a first law in which the area is proportional to the thermodynamic law AE = T S (in its most form without additional potentials and work terms) read as

\[ \Delta M = \Delta A \]

Here the mass of the black hole played the role of thermodynamic energy and the surface gravity \( \kappa \) (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 entropy, as observed earlier. There is a straightforward generalisation to include additional work terms. Moreover, \( \kappa \) was constant over the entire horizon and this was like in the zeroth law of thermodynamics where the temperature is constant at equilibrium. Finally, there was an analogue of the third law in that it is apparently impossible to reduce \( \kappa \) to zero for a black hole through a finite sequence of processes. However, in the black hole case, this was not just an analogy, and the actual condition of a black hole was zero since it could absorb radiation but not emit anything.

Quantum Properties of Black Holes

Jaco Kok, on the other hand, took seriously the observation that black holes can apparently violate the second law of thermodynamics since one cannot put the maximum heat possible into a 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 he proposed that black holes do have a thermodynamic entropy proportional to the area. He proposed a generalised second law of thermodynamics in which the total entropy, namely the usual thermodynamic entropy external to black holes together with the entropy assigned to the black holes, is always non—decreasing. However, Bekenstein was the first [1] to fix the constant of proportionality 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 impassable since they could not emit radiation and only absorb it. During a Moscow visit in 1973, Hawking was influenced by the Soviet astronomer, Vitaly Zel'dovich, who had described a classical phenomenon called superreflexion from rotating black holes and heuristically argued from the quantum uncertainty principle as going rise to a similar phenomenon. Hawking attempted to rigorously incorporate quantum effects in the background of a rotating black hole. To his surprise he found a non—rotating 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

\[ T = \frac{\hbar c}{8\pi MG} \]

where \( M \) 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 (\( k_B \)) and Newton's constant of gravitation (\( G \)). This beautiful formula for the temperature was proportional to \( \frac{1}{\kappa} \) as foreseen by the laws of black hole mechanics and this was a generalisation of Planck's constant in analogy with the Planck's constant. Thus it demonstrates the intrinsically quantum nature of the phenomenon.

This immediately led, via the second law of black hole mechanics to the fourth law of black hole mechanics in the entropy formula of Bekenstein to be fixed— to be what is now called the Bekenstein—Hawking formula

\[ S = \frac{\kappa A}{4\pi} \]

Thus Hawking showed that Bekenstein's proposal didn't hold if we calculated it in a proper quantum taken into account. Classically a black hole appears to be featureless and black but it actually has a quantum mechanical entropy and a resultant black body spectrum of radiation. This underscores the centrality of quantum mechanics in deciphering the nature of black holes. Hawking's calculation opened the window onto the quantum behaviour of gravity. We flush 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.

Shortly thereafter, Hawking realised that the perfectly thermal nature of black hole radiation also created a 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 distribution of radiation is a mixed state (or density matrix) as opposed to a pure state.

However, the unitary time evolution of quantum mechanisms (which is central) to ensure that the sum of all quantum probabilities add up to one) prevents pure states from evolving into density matrices. There aren't then a paradox of how a black hole can be a result of the collapse of matter and differ in the precision of a pure state to evolve into a thermally radiating object. In fact, eventually a black hole can completely evaporate leaving only the radiation behind. This puzzling about which we will have more to say in the next section is called the 'Information Paradox' and continues to be actively debated to this day.

Quantum Effects in Cosmological Spacetimes

Hawking, together with Gary Gibbons, realised in 1974 that certain cosmological spacetimes which have an exponentially accelerated expansion (as shown by Sitter (dS) spacetimes) 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 spacetime is only able to see a part of the spacetime even if the universe is infinitely long since the enormous acceleration takes regions of spacetime out of causal contact with her. What Gibbons and Hawking realised was that such a cosmological event horizon can be assigned an effective Hawking temperature (directly proportional to the surface gravity \( k_B \) and \( M \)) as well as an effective spatial entropy (in effect the area of the two dimensional surface (with the same constant of proportionality as in the black hole case). This area is inversely proportional to the value of the cosmological constant \( \Lambda \). However, the unitary evolution of quantum mechanics (which is central) to ensure that the sum of all quantum probabilities add up to one) prevents pure states from evolving into density matrices. Therefore, the idea of a parallel universe with a different value of \( \Lambda \) cannot be viewed as a means of the observer to the degrees of freedom beyond her horizon.

When these ideas were put forward, de Sitter (dS) spacetime was more of a historical toy example of a cosmological spacetime. It is rather remarkable that forty years later, dS spacetime is central to a number of astrophysical and cosmological. With the discovery of a dark energy component and current day acceleration, the Universe is expected to approach dS spacetime 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, when signals have been measured of 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 spacetime.

Thus when inflation was proposed in the early 1980s, Hawking was one of the first (together with Vyacheslav Mukhanov and others) to realize that quantum fluctuations in dS spacetime 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 original

\[ \frac{dM}{dA} = \frac{c}{8\pi MG} \]

\[ \text{The focus, however, shifts now from the singularity to the really difficult problems of cosmology. This, in turn, led to wrestling with the really difficult problems of quantum gravity i.e. the quantum fluctuations of the recently measured collision of black holes by the LIGO instrument. The work culminated in a very 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 new era was played by the Raychaudhuri equation, derived more than a decade earlier, which demonstrated the focussing effect of gravity on matter which made the formation of singularities inevitable. The use of a local energy condition which captured the positivity of matter energy density showed that the essentially attractive nature of gravity was ultimately what was responsible. The general relativity of the Hawking—Penrose result helped to not only settle the controversy on singularities but also highlighted the power of the new techniques of general analysis that were brought about by the work of the "old" school of thinking which felt these singularities were unavoidable.}\n
\[ \text{The singularity theorems are unavoidable.} \]

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Quintessence theory and Einstein gravity

As we have discussed earlier, 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 at the birth of the universe. How would these singularities be resolved in a quantum theory? We have also discussed his work on the relativistic quantum field theory of elementary particles in the presence of a black hole that led to the notion of thermodynamic entropy for black holes and the ‘information paradox’. In deriving these results, the gravitational field (i.e., the metric of spacetime) 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 account of the black hole entropy without such a microscopic quantum description of gravity. The program to quantize gravity using the Einstein–Mikhter action as a starting point began in the early 1960s and references therein, as well as a photon is a quantum of the electromagnetic field, the graviton, a massless spin two 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 $\frac{\alpha}{\hbar}$, where $\alpha$ is the typical energy of the graviton and $\hbar$ is the Planck constant. This says that at energies $\hbar^2 \sim 10^{19}$ GeV, quantum fluctuations of spacetime are so large that the theory breaks down. Unlike the case of electromagnetism where quantum mechanics regulates the singular behaviour of the 1+1—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 the extensive, volume dependence) of the black hole entropy on its size (as measured by the extent of event horizon). Thus a simple minded quantification of matter and gravity runs into seemingly insurmountable problems. The question then arises whether there is a more fundamental theory that (1) is valid at $\hbar = 0$, and whose low energy $\hbar \rightarrow 0$ limit is Einstein’s theory and (2) is rich enough to account for all the phenomena 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 in the way we explain below. Whether this framework of black hole theory is indeed a more fundamental theory is the subject of current research and development.

In this section we will focus on the problem of addressing the quantum fluctuations of the gravitational field, i.e., spacetime itself, which 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 nature 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 $\exp{\imath S}$, where $S$ is the so—called action of the configuration. 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 $\exp{-\imath S}$.

Hawking advocated a similar Euclidean approach to quantum gravity involving now a sum over all (Euclidean—signature) metric configurations. One of the intentions was to bypass the issue of singularities that arises in the classical theory. To this end he made the ‘no—boundary’ proposal with Jim Hartle, which essentially mentions that one should sum over all Euclidean configurations which are smooth at the past—time singularity. In a sense, they were smoothly capping—off the geometries in the past—like replacing a conical tip by a spherical cap. This would lead to a particular ‘wave function of the universe’, which weights the various geometries at future times (now in Minkowski signature).

While 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 arbitrary large negative values. This is associated with the overall size factor of the metric. This 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 approach to a more fundamental description.

Addressing the Puzzles of Black Holes and Quantum Gravity

Hawkings work on the quantum aspects of black holes gave a very quantitative, for physicists trying to understand the quantum nature of gravity, to aim for some up with a complete and mathematically consistent theory which can microscopically account for the black hole—Hawking entropy of black holes. This has 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 achieved a measure of success towards understanding the questions raised by Hawking’s work. We summarize this narrative below to give a glimpse of how Hawking’s ideas have developed in contemporary physics.

They demonstrated that the Boltzmann entropy of this system is identical to the Hawking—Bekenstein 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 micro—states in terms of a metric field, much as in the Navier—Stokes analogy.

Hawking radiation: Extremal black holes do not Hawking radiate. But the Hawking radiation of a ‘near extremal’ black hole could be microscopically modelled in terms of a slightly excited D0—D∞ system coupled to gravitons by Arvind Dhar, Gaurav Mandal and Spenta Widias, as also Sum Das and Samir Mathur, Cullen Callan 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 a toy model of black holes in supersymmetric string theory the information paradox presented in Hawking’s 1975 paper could be analysed in all detail. It is important to emphasise 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. But 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 plethora of such solutions for which the Strominger—Vafa calculation has been generalised to wish amazing success. It is also important to note that these examples give technically tractable models in which 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 microscopic 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—Sitter (AdS) space—times (with the opposite sign of the cosmological constant from the dS spacetimes mentioned earlier) holographically through a unitary non—Abelian theory on the boundary of the spacetime. This spacetime 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 means that the ‘mean field’ description of many (AdS) 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 non—perturbative theory of quantum gravity in a large class of spacetimes.

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 spacetimes 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 parse out how exactly Hawking’s arguments, made within the framework of string theory, could break the information flow.
of the mean field theory of Einstein equations, break down. Probing deeper has led to an 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.1, 2

Hawking’s work and non—gravitational physics
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 systems that follow from this correspondence. In all of them Hawking’s results play a central role and powerfully demonstrates how far—reaching and profound their impact has been— even on physics which have apparently little to do with gravity.

1. A universal form for the ratio of viscosity to the entropy density of a strongly interacting relativistic fluid is obtained by perturbing a static black hole by an—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.

\[
\eta = \frac{\sigma}{16\pi T_4^2} = \frac{A}{16\pi G_N T_4^3} = \frac{b}{4\pi G_N T_4^3}
\]

In the above we have used the Bekenstein–Hawking entropy formula. This has proved very influential in understanding the physics of the strongly interacting quark–gluon plasma [6]. 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 of real fermions with disorder. This shows how the physics of black hole entropy imply certain universal characteristics for down to earth physical systems!

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.

Hawking very much had a zest for life. During the conference banquet we celebrated his 50th birthday and he danced with his wife — swirling his chair around and back and forth. A vivid memory of his visit is the warmth and care he showed towards the many, 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 made possible by Mr S. D. Shibulal of Infosys Technologies, an alumnus of TIFR. He so generously and so promptly agreed to pay for the expenses involved in bringing Hawking to India. Without this it would not have been for Hawking to travel to India as many other potential donors from Mumba could not come forward. Anand Mahindra provided a special vehicle for Stephen.

One important outcome of Hawking’s visit 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. Hawking’s presence in the country was quite a sensation and the media was in full swing about him, including 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 Shri Ram Mitha Mandir Hall in new Delhi, and the huge hall was filled to capacity!

Hawking and Science Popularisation

Hawking was indeed a great global ambassador for fundamental science. Through 'The Brief History of Time', a very engaging series of books aimed at sparking the interest of children in science was co-authored with his daughter Lucy Hawking. In addition, the vast number of portraits and the conundrums of quantum gravity, Rajesh Gopakumar, Current Science, Vol. 99, No. 9, p. 1253—1267, 2008; arXiv:0809.1036


A very engaging series of books which updated and elaborated on The Brief History of Time. A very engaging series of books which updated and elaborated on The Brief History of Time. A very engaging series of books which updated and elaborated on The Brief History of Time. A very engaging series of books which updated and elaborated on The Brief History of Time. A very engaging series of books which updated and elaborated on The Brief History of Time.
PROGRAMS

Living Matter
16–26 April 2018 Organizers — Vidyanand Nanjundiah and Olivier Rivoire

Third Bangalore School on Population Genetics and Evolution

Nonperturbative and Numerical Approaches to Quantum Gravity, String Theory and Holography

Kavli Asian Winter School (KAWS) on Strings, Particles and Cosmology 2018
8–18 January 2018 Organizers — Munir Hasan, Sagnik Sen, Sunil Gupta, Pathik Mitra and Rima Panigrahy

Consultation on National Education Policy (NEP) 2017
2–7 December 2017 Organizers — M. Mallik Bhalerao, Manjul Bhargava, Leena Chandran-Wadia and Spenta R. Wadia

Surface Group Representations and Geometric Structures
27–30 November 2017 Organizers — Siddhartha Gadgil, Krishnendu Gogoi and Spenta R. Wadia

Collective dynamics of—on and around Filaments in Living Cells — Motors, M&Ps, TIPS and Tracks
28 October—2 November 2017 Organizers — Tameem Husain, Anirban Kumar and Prabal K Maiti

Lecture Series

INFOSYS—ICTS TURING LECTURES
Evolutionary Dynamics and Diversity in Large Populations
8 March 2018 Speaker — Daniel S Fisher (Stanford University, USA)

The evolution of individuality and why life is hierarchically structured
13, 14, 15 December 2017 Speaker — Paul B Ruitz — Department of Microbial Population Biology, Max Planck Institute for Evolutionary Biology, P¨and, Germany, Laboratoire de G´ene´ticaire de l’Evolution, EPFL Paris, France & The New Zealand Institute for Advanced Study, Massey University, Auckland, New Zealand

INFOSYS—ICTS CHANDRASEKHAR LECTURES
Computing Reality
31 January 2018 Speaker — David B. Kaplan (University of Washington, USA)

5. Chandrasekhar’s fluid dynamics
22 January 2018 Speaker — Kasturi Raju Snehinathan (Dean of NYU Tandon School of Engineering; The Eugene Kleinberg Professor for Innovation in Mechanical Engineering; Professor of Physics (Faculty of Arts and Sciences); Mathematics (Courant Institute of Mathematical Sciences))

Symmetries, Duality, and the Unity of Physics
8 January 2018 Speaker — Tullio De-Silber (Institute for Advanced Study, School of Natural Sciences, Princeton, New Jersey, USA)

INFOSYS—ICTS DISTINGUISHED LECTURE
Mysteries Of The Higgs Boson
17 April 2018 Speaker — Michael E. Peskin (SLAC, Stanford University)

Symmetry in Quantum Gravity
15 January 2018 Speaker — Hiroshi Ooguri (Fred Kavli Professor of Theoretical Physics and Mathematics, Director of the Walter Burke Institute for Theoretical Physics, Caltech, Principal Investigator, Kavli IPMU, The University of Tokyo and President, Aspen Center for Physics)

The SYK Model (Kavli Distinguished Lecture)
8 January 2018 Speaker — David Gross (KITP—University of California, Santa Barbara)

PUBLIC LECTURES
Can Evolution be Understood Quantitatively?
6 March 2018 Speaker — Daniel S Fisher (Stanford University)

The Science of the Man from the 9 Dimensions
14 January 2018 Speaker — Illusor Ooguri (Fred Kavli Professor of Theoretical Physics and Mathematics, Director of the Walter Burke Institute for Theoretical Physics, Caltech, Principal Investigator, Kavli IPMU, The University of Tokyo and President, Aspen Center for Physics)

The Usefulness of Useless Knowledge
7 January 2018 Speaker — Robert Hooke (IAS, Princeton)

Deciphering the Workings of Molecules, Building Blocks of Life, With the Electron Microscope
1 November 2017 Speaker — Joachim Frank (Columbia University, New York)

Joachim Frank won the 2017 Nobel Prize for Chemistry. This was his first public lecture since winning the Prize.

EINSTEIN LECTURES
In Brightest Day and Blackest Night
26 February 2018 Speaker — Kazi Adhikari (Professor of Physics, Caltech) Venue — Library Auditorium, BMS College of Engineering, Bangalore

Stephen Hawking’s Legacy in Fundamental Physics
24 April 2018 Speaker — Rajesh Gopakumar (ICTS-TIFR) Venue — Infosys Campus, Electronic City, Bangalore

VISVESVARAYA LECTURES
ICTS has introduced a new lecture series, celebrating the life and work of C.V. Visvesvaraya — a pioneer in black hole physics and science outreach in India. The Visvesvaraya Lectures will be delivered by leading scientists who have also contributed greatly to communicating science to the public.

Exploring the Universe with Gravitational Waves — From the Big Bang to Black Holes
13 January 2018 Speaker — Sidney M. Yang (Yerkes Professor of Theoretical Physics at Caltech) Kip Thorne won the 2017 Nobel Prize for Physics.

KAAP WITH KURISUDY
Endless Forms Most Beautiful
25 March 2018 Speaker — Sharan önüne Obison (National Centre for Biological Sciences, NCBS, TIFR) Venue — J. N. Planetarium, Bangalore

Fascinating world of photons, superradiation and entanglement
25 February 2018 Speaker — Urbasi Sinha (Quantum Information and Computing (QuIC) Laboratory at Research Institute for Nanotechnology, Bangalore) Venue — J. N. Planetarium, Bangalore

Black Holes
21 January 2018 Speaker — Ramesh Narayan (Thomas Dudley Cabot Professor of the Natural Sciences at Harvard University and Senior Astronomer at the Smithsonian Astrophysical Observatory) Venue — J. N. Planetarium, Bangalore

Paloecology — the modern legacy of ancient viruses
10 December 2017 Speaker — Hamid Malik (Fred Hutchinson Cancer Research Center, Seattle, USA) Venue — J. N. Planetarium, Bangalore

Shapes and geometry of surfaces
26 November 2017 Speaker — Mahan Mj (TIFR, Mumbai) Venue — J. N. Planetarium, Bangalore

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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