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CELEBRATING THE UNITY OF SCIENCE : ICTS TURNS 10

4–7 January, 2018 | Discussion Meeting

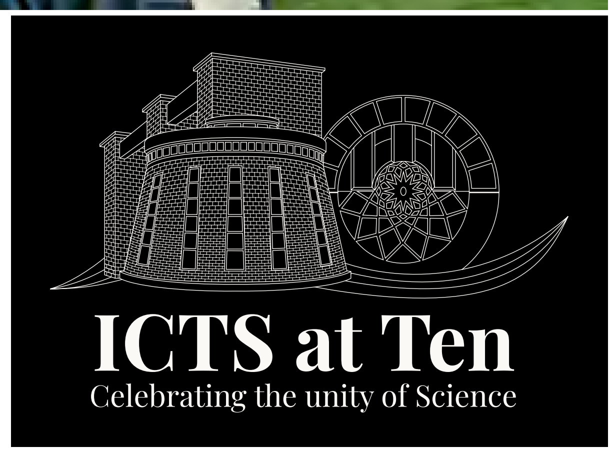
ICTS at Ten

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. ■

Below here and on the next page, are a few glimpses from the discussion meeting, *ICTS at Ten*.



7 January, 2018 | Public Lecture and Panel Discussion

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 humankind.

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 Wadia**. The panelists were **Manjul Bhargava** (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). ■






The list of speakers can be found at www.icts.res.in/discussion-meeting/icts-at-ten
All the *'ICTS at Ten'* lecture videos are available on the ICTS YouTube channel – www.youtube.com/channel/UCO3xnVTHzB7I—nc8mABUJIQ

11 January, 2018 | ICTS Vishveshwara Lecture

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'*.

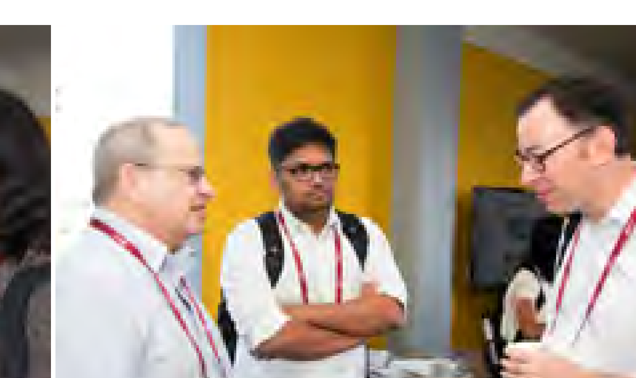
Thorne talked about the two types of waves that can propagate across the universe: Electromagnetic waves and gravitational waves. Galileo initiated electromagnetic astronomy 400 years ago by pointing a telescope at the sky and discovering the moons of Jupiter. LIGO recently initiated gravitational astronomy 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. ■

14 January, 2018 | Public Lecture & Movie

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 struggling 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 quantum theory of gravity, was found. Twenty years ago, a remarkable discovery came out of string theory: quantum mechanics and general relativity are not actually two 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 it is so exciting.

I will start by explaining a few essential aspects of quantum mechanics and general relativity. Quantum mechanics (QM), which is necessary for an accurate description of systems on atomic and smaller length scales, radically alters our notion 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, according to the famous Heisenberg uncertainty principle in QM it 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 at the root of many of the counterintuitive features of QM; this was emphasized by Einstein, who called it "spooky action at a distance". It also plays a central role in technologies powered by quantum mechanics, such as quantum cryptography and quantum computation.

We now turn to general relativity (GR). This theory, which is necessary for an accurate description of systems on the scale of the solar system and larger, radically alters our notions of space and time: these are united in a single four—dimensional continuum, whose geometry is variable and dynamic, responding to the matter embedded in it, while dictating how that matter moves. This interaction between spacetime geometry and matter gives rise to the force of gravity.

Although clearly a part of modern physics, GR is labelled by physicists as a "classical" theory, by which we mean that it does not obey the rules of QM: the variables specifying the geometry of spacetime, as well as the positions and momenta of particles in spacetime, take on definite values. The problem of combining GR and QM, in other words of finding a consistent quantum theory of gravity, is famously difficult, and has been partly solved by string theory. "Partly" means that, while string theory in principle is a fully consistent quantum theory of gravity, and while we can use it to do certain calculations that simultaneously involve QM and GR (for example, involving scattering of gravitons, the particles that carry the force of gravity), we do not yet have a complete understanding of the theory. For this reason, string theory has not yet answered many of the thorniest questions at the intersection of QM and GR, such as the black—hole information puzzle or the nature of the big bang. We also don't yet know whether the real world is actually described by string theory, or by some other quantum theory of gravity.

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,

Fig. 1: According to the holographic correspondence, certain two—dimensional quantum—mechanical (QM) systems are equivalent to three—dimensional general relativity (GR). The plane where the QM system lives is the top boundary, shaded in blue, of the GR space. The latter space is warped, with distances being larger than they appear near the top and smaller near the bottom. According to the Ryu—Takayanagi formula, if we divide the QM plane into two parts, then the degree of entanglement between them is given by the area of the minimal surface anchored on their mutual boundary———here, the red circle. Because of the warped geometry, this minimal surface, shown in orange, hangs down rather than stretching flat across the circle as one might expect.

spacetime has a fixed geometry and there is no force of gravity. Yet Maldacena showed that they admit a radically different alternative 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 extra dimension of space compared to the QM description. For example, in certain cases the QM system lives in ordinary three—dimensional space while the GR description has four spatial dimensions. In others cases, 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 QM, 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. However, concrete and useful descriptions of this collective behavior were lacking before Maldacena. The fact that this description in some cases is GR, with an extra dimension of space, was completely unexpected, and remains deeply mysterious.

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. Theories with strong interactions are very difficult to study by traditional theoretical methods. However, their equivalence to GR makes them relatively tractable, because classical theories are almost 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 colliding atomic nuclei to high—temperature superconductors. Conversely, holography also provides a new perspective on GR and gravity. While the GR theory that governs holographic systems is not 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 our universe, 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 features of QM that most sharply distinguishes it from classical mechanics. If we take a holographic system and consider it in the QM description, then its different parts will naturally be highly entangled with each other. Does that entanglement manifest itself somehow in the GR description? Given that GR is classical and therefore does not admit the possibility of entanglement, one might think that it cannot. Surprisingly, however, the answer is yes. Not only does the entanglement manifest itself in GR, it does so in a beautiful, geometrical way. In 2006, Shinsei Ryu and Tadashi 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 geometry on 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 loop of wire will arrange itself into a minimal surface. The mathematical problem of finding minimal surfaces is called the Plateaux problem. Ryu and Takayagani 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 a surface area, Ryu and Takayanagi were 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 2006, the study of holographic entanglement has multiplied in many directions. Since Ryu and Takayanagi essentially guessed their formula, rather than deriving it, a major thrust initially was to check its validity by comparing its predictions both against first—principles calculations and against known general properties of entanglement. It passed all of these tests with flying colors, and this process deepened our understanding of holographic entanglement considerably. Another major thrust has been to generalize the formula, in order to make it as broadly applicable as possible. For example, initially it described only static states, but subsequent work by Veronika Hubeny, Mukund Rangamani, and Takayanagi generalized it to dynamical processes. Their version has been used, for example, to better understand how certain systems thermalize. The formula has been applied extensively to holographic models of real—world systems, such as nuclear matter and superconductors, in order to understand their physics better. At a more fundamental level, one school of theorists, led by Mark Van Raamsdonk, has posited that entanglement should be viewed as the basic building block of holography, 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 Ryu—Takayanagi formula.

More generally, Ryu and Takayanagi's discovery has revealed a deep and rich connection between GR and quantum information theory. By now, this connection has been extended far beyond just entanglement to touch on such concepts as quantum error correction, tensor networks, and algorithmic complexity. In fact, interesting new developments in quantum information theory have already been spurred by its connections to holography. String theorists and quantum information theorists now routinely meet at conferences and collaborate on papers, a state of affairs that would have been hard to imagine fifteen years ago.

In my view, the discovery 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. SATHYAPRAKASH

The 2017 Nobel Prize in physics was awarded to Rainer Weiss, Barry Barish and Kip Thorne *'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 meticulous observations by Tycho Brahe and his assistants in the 16th century to discover that planets, instead of being *random wanderers*, followed predictable paths. One of Brahe's assistants was Johannes Kepler, whose careful analysis of the data revealed the three laws of plenary 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 theory of gravity.

What made these deductions possible was not just the design and construction of astronomical instruments (such as, the quadrant and sextant), but their precise and periodic calibration. The latter allowed positions of planets to be recorded to phenomenal accuracies of an arc minute or less. Measurement accuracies have been critical for breakthroughs throughout the history of science. Indeed, astronomical observations made over more than one—hundred years showed that Mercury's elliptical orbit around the Sun was not fixed but exhibited apsidal precession. A systematic analysis of the data led Urbain Le Verrier in France to conclude in 1859 that Newtonian gravity could not fully account for the measured precession of 575 arc seconds per century. He worked out that the tidal tug of the outer planets contributed 532 arc seconds. To explain the apparent discrepancy between observation and theory, Le Verrier proposed the existence of an unseen planet even closer to Sun than Mercury that could produce the necessary tug. However, no such object was ever found and the precession of perihelion remained a puzzle for half—a—century.

Enter Einstein

In the end, Einstein was able resolve precession of perihelion of Mercury in 1915 with his new theory of gravity, the *general theory of relativity*. In this theory, all forms of matter and energy can produce gravity including gravitational energy itself. This nonlinearity of gravity, Einstein showed, could fully explain the orbital motion of Mercury.

Einstein's theory has had deeper impact on our understanding, not just of gravity but the very structure of space and time. According to Newton, space is rigid, time intervals are absolute, and physical interactions that take place in the immutable arena of space and time don't affect it 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 '*matter tells spacetime how to curve and in turn spacetime tells matter how to move.*' What is this curvature of space and time?

Warped and Dynamical Spacetime

Warpage of space causes proper distances[1] 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 the warpage of spacetime to change as well. The change in warpage, according to Einstein, propagates from the source at the speed of light and these will be seen as causing change 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 strain* $h = \Delta L/L$ they cause in the distance L between free masses.

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 even Einstein 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 (e.g., the metric tensor) endowed with more degrees of freedom than were physically necessary so that the theory could be used by all observers, whether they were in an inertial or non—inertial reference frame[2]. General relativistic equations are valid for all observers but there is a prize to pay: one has to deal with many spurious quantities and recognizing the true physical degrees of freedom took decades after the theory was formulated.

Theoretical work by Herman Bondi, Felix Pirani and Igor Robinson in the late 1950's resolved conceptual difficulties that plagued theorists for decades, by showing that wave degrees of freedom in general relativity were not spurious but carried real physical energy, 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.

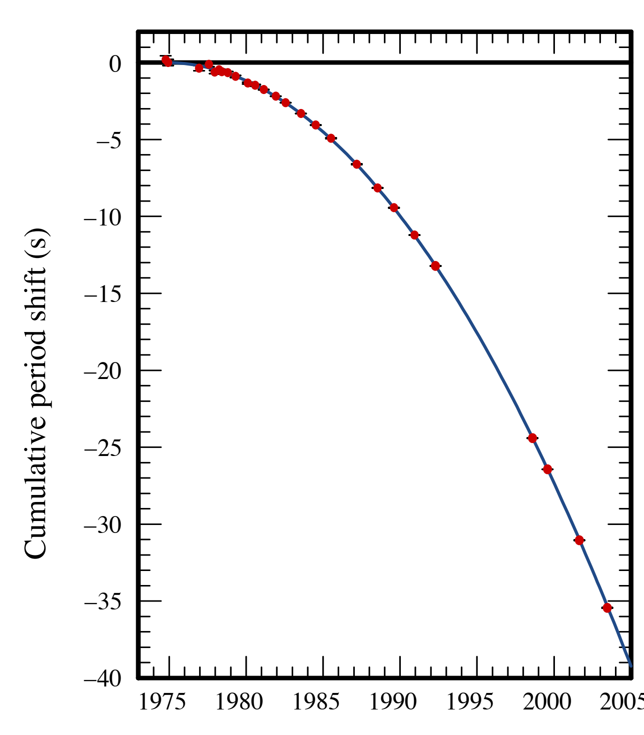


Fig. 1: The plot shows cumulative shift of periastron time, which decreases in time due to decrease in the orbital period

First Observational Evidence

First concrete evidence for the existence of gravitational waves came from radio observations of a binary pulsar system called PSR 1913+16, discovered by Russel Hulse and Joseph Taylor in 1976. This binary consists of two neutron stars, each of mass approximately 1.4 times that of Sun, in an elliptical orbit around each other, with a period of about $P \sim 7.75$ hours. General relativity predicts that due to loss of energy and angular momentum to gravitational waves the orbital period should change by 76.5 microseconds each year.

Because PSR 1913+16 is in an elliptical orbit it is possible to use the point of closest approach, or periastron, as a reference point to monitor the change in the orbital period of the system. If the orbital period is constant, as one would expect in Newtonian gravity, the two stars would be at periastron after any integer multiple of the period P_R *measured at some reference time*. So, after a time $T = n\,P_R$, the binary should have completed n orbits or $n\,P_A - T$ should be zero, where P_A is the actual period – the time interval between two consecutive periastron passages. If, however, the period decreases then $n\,P_A - T$ would be negative. As shown in Figure 1, the data shows a steady decrease in the orbital period, exactly as predicted by Einstein's theory of gravity.

Strongest Sources

In general relativity, the magnitude of curvature produced is proportional to mass and energy density of matter. The constant proportionality is G/c^4, where G is Newton's gravitational constant and c is the speed of light. It has dimensions of 1/force. This force is enormous: $GF \equiv c^4/G \simeq 10^{44}$ N. It implies that only when stresses in a system are large enough to produce forces this big can we expect the warpage of spacetime to be perceptible. So, 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 rotational speed v. The centripetal force experienced by the two stars is $F = Mv^2/r = v^4/G$, where r is the distance between the bodies. In the last of the equalities I have used Kepler's second law $v^2 = GM/r$. We can rewrite the centripetal force as: $F = G_F\,(v/c)^4$. Since v is less than c, the centripetal force is always smaller than G_F, coming close to it when $v \sim c$.

To make v close to c 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 far before v can approach c. However, in the case of black—hole and neutron—star binaries, together referred to as compact binaries, v can get close to c 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 from an astronomical binary of massive stars. Central regions of stars are very hot. They burn hydrogen, helium and other elements to produce high energy radiation at their cores. The resulting radiation pressure holds stars from collapsing against their own gravity. A binary black hole or neutron star could form when 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 would be initially 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 millions of years get so close that their speeds 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 squeeze 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 monitoring the distance between free test masses one can, in principle, detect gravitational radiation. However, even the most powerful events cause a miniscule change (less than 1/1000 of the diameter of a proton) in distance between test masses that are separated by a few kilometers. Detecting such length changes is a formidable technical challenge.

Rainer Weiss was among the first to realize that Michelson interferometers, that are routinely used to measure the speed of light in a physics lab, could be used to detect gravitational waves. He also recognized the hurdles that one must overcome in making a sensitive detector and how they might be mitigated. The basic principle behind these detectors is to measure the differential change in length of the interferometer arms using a high—power laser and mirrors suspended at the ends of the 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 as an observational tool. The idea was similar to extending astronomical observations from optical to infrared radiation, radio waves, x—rays, gamma—

Fig. 2: LIGO Hanford *(left)*, LIGO Livingston *(middle)* and Virgo *(right)* interferometers. LIGO detectors both have 4km arms while Virgo has 3km arms.

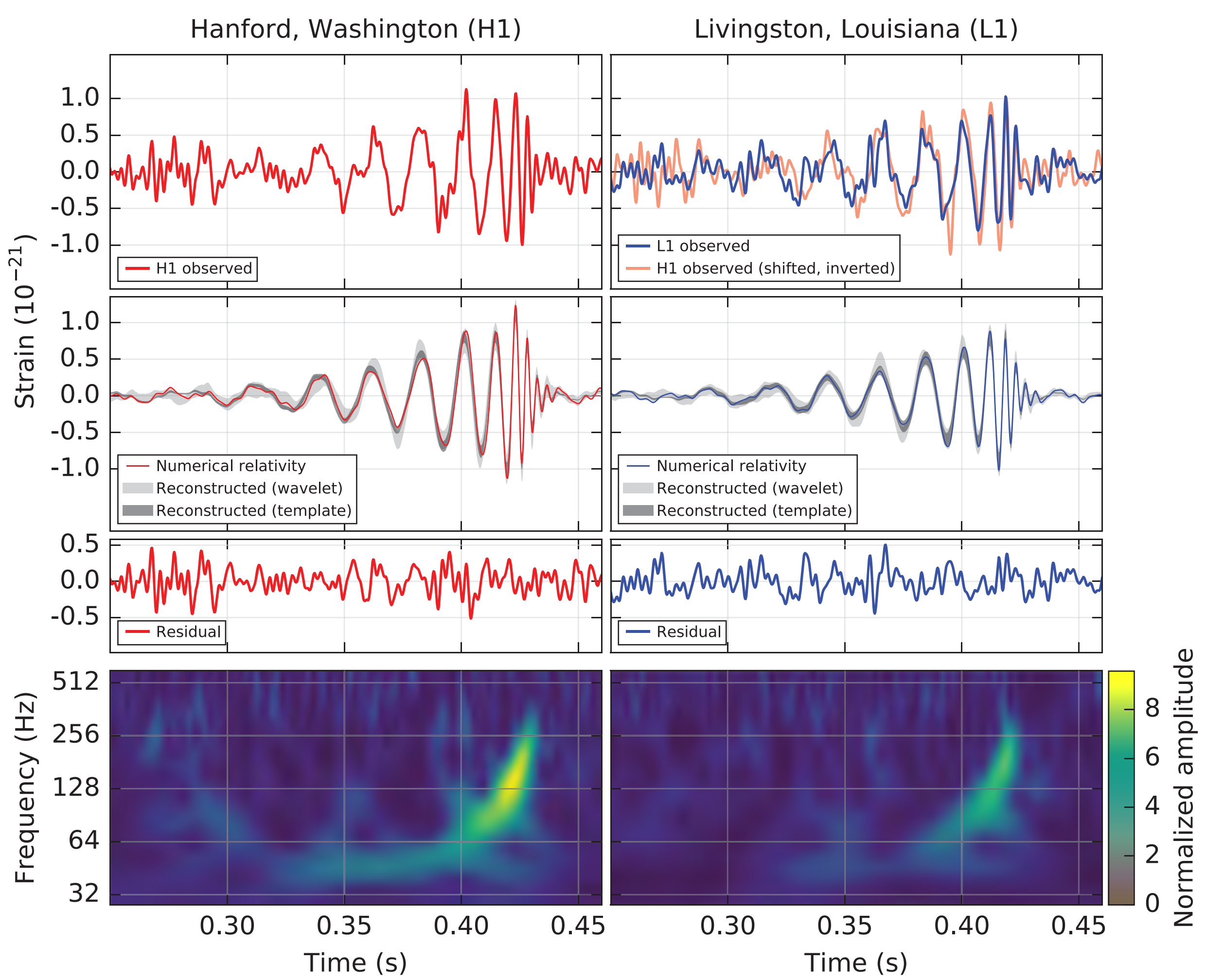


Fig. 3: The gravitational—wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (right column panels) detectors. Times are shown relative to September 14, 2015 at 09:50:45 UTC. For visualisation, all time series are filtered with a 35—350Hz bandpass filter to suppress large fluctuations outside the detectors' most sensitive frequency band, and band—reject filters to remove the strong instrumental spectral lines seen in the spectra.
Top row, left: H1 strain. *Top row, right*: L1 strain GW150914 arrived first at L1 and $6.9^{+0.4}_{-0.5}$ms later at H1; for a visual comparison, the H1 data are also shown, shifted in this time by this amount and inverted (to account for the detector's relative orientations).
Seconds row: Gravitational—wave strain projected onto each detector in the 35—350 Hz band. Solid lines show a numerical relativity waveform for a system with parameters consistent with those recovered from GW150914 confirmed to 99.9% by an independent calculation. Shaded areas show 90% credible regions for two independent waveform reconstructions. One (dark grey) models the signal using binary black hole template waveforms. The other (light grey) does not use an astrophysical model, but instead calculates the strain signal as a linear combination of sine—Gaussian wavelets. These reconstructions have a 94% overlap.
Third row: Residuals after subtracting the filtered numerical relativity waveform from the filtered detector time series.
Bottom row: A time—frequency representation of the strain data, showing the signal frequency increasing over time.

	GW150914	LVT151012	GW151226	GW170104	GW170609	GW170814
Signal—to—noise Ratio	24	10	13	13	13	15
Primary weight	36	23	14	31	12	31
Companion mass	29	13	8	19	7	25
Remnant mass	62	35	21	49	18	53
Effective spin	—0.06	0.03	0.21	—0.12	0.07	0.06
Remnant spin	0.68	0.66	0.74	0.64	0.69	0.70
Distance in Mpc	420	1020	440	880	340	540

Table I: Properties of binary black holes detected so far. GW170814 was detected by both LIGO and Virgo, all others were detected by the two LIGO detectors. All masses are given in units of solar mass.

rays but also neutrinos and cosmic rays.

LIGO was built at two sites in the United States, Livingston LA and Hanford WA, under the leadership of Barry Brish, who served as its director from 1996 to 2006. With 4 km arms, LIGO is the largest and most sensitive detector in the world. France and Italy jointly built Virgo, near Pisa, Italy. Virgo is also an interferometric detector and consists of 3 km arms. Figure 2 shows aerial views of these detectors.

First Observation and Discovery

LIGO and Virgo were operated during 2006—2010 and jointly took data for over a year. During the initial operation, they failed to make any detection. This was not surprising as theoretical calculations had indicated that it would be necessary to improve the sensitivity beyond initial LIGO to make a firm detection. Coalescence of binary black holes and neutron stars are very rare phenomena and occur only once in about a million years in a typical galaxy. Therefore, it was essential that the detectors were sensitive enough to observe sources from a cosmological volume that contained millions of galaxies before a detection could be made.

Both LIGO and Virgo began upgrading around 2010. After the upgrade, LIGO began its first observing run (or O1) in September 2015 and in the very first week of its operation observed gravitational waves from the inspiral and merger of a pair of black holes in a galaxy 1.3 billion light years from Earth. The signal first arrived in Livingston and 7 milliseconds later in Hanford.

The signal observed in Livingston and Hanford (after shifting the Hanford signal to account for the time—delay and swapping the sign because Hanford's interferometer arms are oppositely oriented relative to Livingston) is shown in Figure 3. Also plotted is the prediction of general relativity that best fits the data. Starting from a frequency of 30 Hz, the signal lasted for about 200 milliseconds and 10 gravitational wave cycles (or just 5 orbits). The amplitude of the signal grows until it reaches a frequency of about 300 Hz, after which the signal dies out exponentially. The only interpretation for the sudden disappearance of the signal is that two bodies that produced the signal merged with each other and thus stopped rising ripples in the curvature of spacetime.

From the frequency at which the signal amplitude peaked we can deduce the total mass of the system and this turns out to be about 65 solar masses. From the rate at which the signal's frequency increases from 30 Hz to 250 Hz we can compute a combination of the component masses called the chirpmass[3], which turns out to be 28 solar masses. These two measurements imply that the component masses are 29 and 36 solar masses. In Figure 3, the largest gravitational—wave frequency we see is about 250 Hz and this corresponds to an orbital frequency (which is half of the gravitational—wave frequency) of 125 Hz. From Kepler's law, we conclude that the radius of the orbit, for a total mass of 65 solar masses, is about 240 km.

The orbiting masses must therefore be at best half of orbital radius, or 120 km. At the present time, the only objects that we know that are so massive and occupy so little space are black holes. This does not mean they are not anything else. It will take many years before we can be certain that objects this big are not some other exotic objects. The mass of the merged black hole was determined to be 62 solar mass. This is 3 solar mass less than the total mass of the progenitor binary and was entirely converted to gravitational radiation – pure oscillation of spacetime.

Indeed, LIGO's debut event constitutes a triple discovery: the first direct detection of gravitational waves, first observation of a black hole binary and first recording of the birth of a new black hole. Before LIGO's discovery, astronomers believed that black holes that formed from stars could not be heavier than about 20 solar masses. LIGO's discovery has already caused a paradigm shift in how we now think black holes might form in the Universe.

During the first observing run in 2015, LIGO observed two other black hole binary mergers, a highly significant event GW151226 on December 26 and a statistically less significant event LVT151012 on October 12 (see Table I), confirming that the first discovery was not a one—off, rare event, and that LIGO had begun a new observational era in astronomy.

And Then There were Three

LIGO ended O1 in Jan 2016 and began its second observing run (or O2) in November 2016. Between November and July LIGO discovered two more binary black hole mergers, GW170104 and GW170608 (see Table I). Virgo joined O2 in August 2017. Addition of a third detector to the network was a landmark event as at least three non—collocated detectors are required to fully reconstruct the properties of an 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 I 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 queer that black hole effective spins (see Table I) are all 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 titled 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 not easy for stars to turn into non—spinning black holes; they have to get rid of their large angular momentum before they collapse. Finally, it is plausible that we are observing the merger of primordial 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 mechanism of these black holes.

Gravitational wave detectors can localize sources on the sky by triangulation, which requires at least three detectors to accurately pin point the source. With the two LIGO detectors it was not possible to localize the source to better than about 1200 square degrees. When Virgo joined LIGO in August 2017, the very first source they jointly detected was the merger of a pair of black holes of 25 and 30 solar masses at a distance of about 540 Mpc and the source was localized to within 60 square degrees. Moreover, for the first time it was possible to measure the polarization of the waves, which turned out to be consistent with the prediction of general relativity.

Observation of a Binary Neutron Star Inspiral

LIGO and Virgo were built to observe coalescence of neutron stars, the final few minutes in the life cycle of a system similar to PSR 1913+16. The merger of such a system, it has long been speculated, would not just produce a burst of gravitational waves but the aftermath of the merger would result in a cosmic firework in the entire electromagnetic spectrum, from gamma—rays and x—rays, all the way to optical, infrared and radio waves. Of great importance among these is the radiation that is produced by the formation and decay of heavy elements (heavier than iron; lanthanides, for example) by rapid neutron capture process, in the hot and high energy eject that is produced in the aftermath of the collision of the two neutron stars. Detailed calculations showed that neutron star collisions could well be the environments in which heavy elements like gold, silver, platinum, uranium, etc., found here on Earth are produced.

In fact, binary neutron star mergers were believed to be progenitors of short gamma—ray bursts (SGRBs), intense flashes of high energy gamma radiation that last for only a second or two and yet could be seen

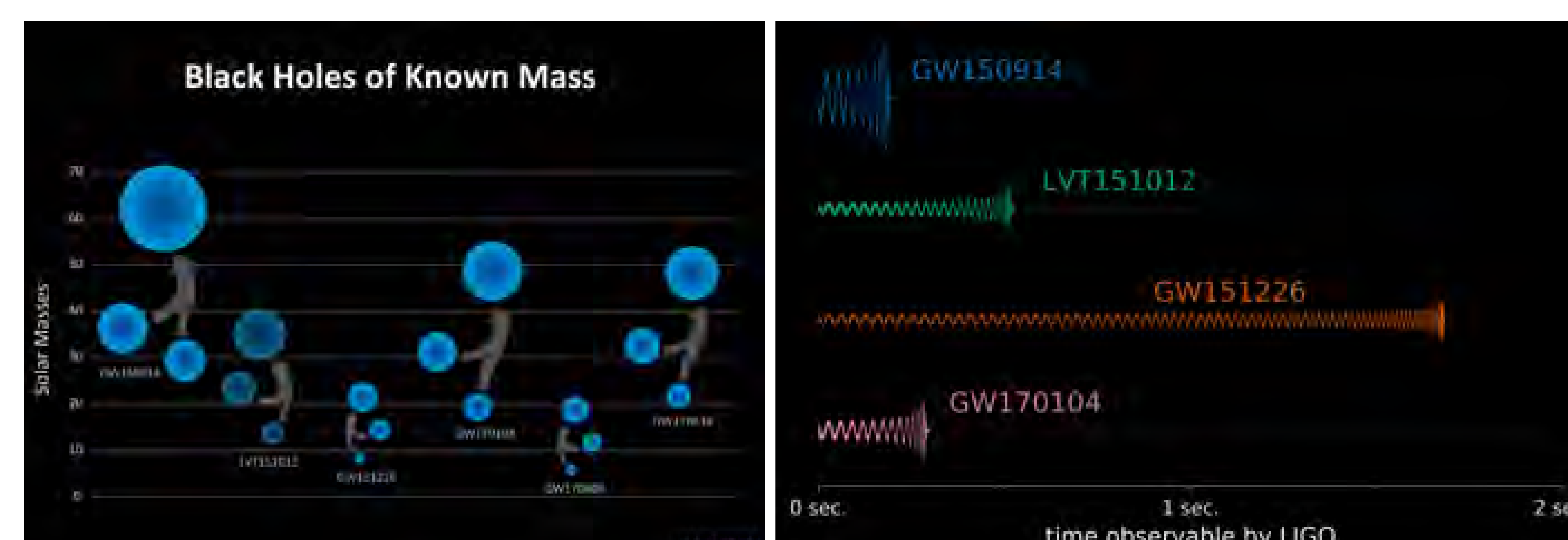


Fig. 4: Black holes observed in gravitational waves. The left panel shows masses of binary companions and of the merger remnant. The right panel shows gravitational waveforms for the first four detections as observed by LIGO.

at billions of light years from Earth. Although gamma ray observatories like SWIFT, INTEGRAL and FERMI have detected scores 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 to commission further sensitivity improvements, finally saw the observation of a binary neutron star merger. This event literally shook the world. Dubbed GW170817, it is the loudest event recorded by our detectors so far and came from the merger of a pair of neutron stars of masses roughly in the range1.2 and 1.6 solar masses. LIGO and Virgo localized the source to within 28 square degrees in the constellation of Hydra, and measured the distance to be about 40 Mpc. FERMI and INTEGRAL gamma—ray observatories recorded a short burst just 1.7 s after the merger thus confirming the long—held view that SGRBs came from the coalescence of neutron stars. The event was identified by optical and infrared telescopes within 10 hours of the merger, placing the event in the galaxy NGC4993. These observations also confirmed the formation of heavy elements that was predicted more than five decades before. In total, more than 70 astronomical groups around the world followed up GW170817 and confirmed that the event produced x—rays, UV, optical, infrared and radio waves, just as astrophysicists had predicted years before.

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 also emits gravitational waves. This radiation is not expected to be strong but we do not know how weak that might have been and if it conforms with theoretical predictions as no post—merger oscillations have been detected. We also do not know how long the bar—shaped merger remnant lasted as an unstable, hyper—massive neutron star, 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.

Future of Gravitational—Wave Astronomy

In just two years since their first operation, Advanced LIGO and Advanced Virgo have made discoveries that have given us a wealth of new information about dynamical spacetime. They have established a new window for observing the Universe and begun to transform our understanding of the formation and evolution of black holes. When they reach their design sensitivity, LIGO and Virgo will routinely observe the gravitational—wave sky and discover new processes and phenomena in the local Universe. It is no surprise that 2017 Nobel Prize was awarded to the pioneers of this exciting new discovery.

Even more sensitive detectors would be required to solve some of the most enigmatic questions in fundamental physics, nuclear physics, astronomy and cosmology. What is the nature of highly deformed horizons and are black holes the true end states of gravitational collapse? What is the structure of neutron star cores and is there a state of stable matter beyond nucleons that can hold out against gravitational collapse? When did first black holes form and how did they grow to become millions to billions of solar masses found in nuclei of galaxies? What drove the expansion of the Universe throughout cosmic history, is it dark energy (cosmological constant or its variants) or modification of general relativity that can explain the recent accelerated expansion of the Universe? These are among questions upon which gravitational wave detectors such as the Einstein Telescope and Cosmic Explorer, detector concepts that are currently being studied, could provide some insights.

Acknowledgements

I would like to thank my colleagues in the LIGO and Virgo Scientific Collaborations for many useful discussions on gravitational waves and for Figures 2—4 used in this article.

Further Reading

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[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 one would need to add fictitious forces to get Newton's laws to work.

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

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BETWEEN THE SCIENCE

PARAMESWARAN AJITH was named the 2017 CIFAR Azrieli Global Scholar. He is the only Indian researcher among fifteen early career researchers to receive this prestigious two—year appointment.

ABHIRUP GHOSH received the Ramkrishna Cowsik Medal of TIFR. This medal is given across the TIFR system for the best paper published in the last three years to researchers under the age of 35. Abhirup was awarded for his work on a test devised by him and collaborators, of Einstein's general theory of relativity using the measurements of LIGO.

RAMA GOVINDARAJAN was awarded the Platinum Jubilee Award of the Aerospace department of IISc. This is awarded to the alumni of the department, who have made significant contributions in the field.

SUVRAT RAJU was awarded the Swarnajayanti Fellowship from the Department of Science and Technology (DST) to advance the research on '*information paradox*'.

SPENTA WADIA was named the ICTS Homi Bhabha Chair Professor of the Infosys Foundation.

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 ALS or Lou Gehrig's disease — a degenerative motor neuronal disorder. Though 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 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 a voice synthesiser, 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 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 [1], Hawking 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 very 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 remarkable trajectory with broadbrush strokes. It begins with his fundamental work on singularities in the classical 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.

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 quantum gravity i.e. the quantum fluctuations of spacetime 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 edged understanding of quantum cosmology.

The singularity theorems

Many of the known (and physically interesting) exact solutions of Einstein equations possess what is known as a singularity. This is a region of spacetime beyond which the spacetime 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 behavior include the Robertson—Walker metric for describing the expanding universe, the Schwarschild and Kerr solutions for describing spherically symmetric and rotating black holes, respectively etc. In the sixties there was a dominant school 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.

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 proof 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 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 the tools now existed to address their general behaviour, this is what Hawking next turned his attention onto. The focus, however, shifts now 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 spacetime 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 focussing 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 spacetime 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, when two black holes collide, to be $(1-\frac{1}{\sqrt{2}})$ or about 30 per cent. 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 per cent)!

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 spacetime) is completely characterised 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. But it was the area theorem which led Hawking, in work with Jim Bardeen and Brandon 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. But 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) read as

$$\Delta M = \kappa\, \Delta A \qquad (1)$$

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 generalisation to include additional work terms.). Moreover, κ was constant over the entire horizon and this was like in the zeroth law of thermodynamics where the 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 others stressed 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 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 did not have any reliable way 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 impossible since they could not emit radiation and 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 quantum uncertainty principle as giving 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 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

$$T_H = \frac{\hbar c^3}{8\pi G_N M k_B} \qquad (2)$$

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_B) and Newton's constant of gravitation (G_N). This beautiful formula for the temperature was proportional to κ ($\propto \frac{1}{G_N M}$) 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, via 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

$$S_{BH} = k_B \frac{A}{4G_N \hbar c^3} \qquad (3)$$

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 black body 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.

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 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 about which we will have more to say in the next section is called the 'Information Paradox' and continues to be actively debated to the present day.

Quantum effects in cosmological spacetimes

Hawking, together with Gary Gibbons, realised in 1977 that certain cosmological spacetimes which have an exponentially accelerated expansion (known as de 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 she waits 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 and h 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, 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 modern cosmology. With the discovery of a dark energy component and current day acceleration, the Universe is expected to approach de Sitter 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, 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 spacetime!

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 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 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. spacetime 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 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 $e^{i\frac{S}{\hbar}}$ 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 $e^{-\frac{S}{\hbar}}$.

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 putative 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 arbitrarily 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 approximation to a more fundamental description.

Addressing the Puzzles of Black Holes and Quantum Gravity

Hawking's work on the quantum aspects of black holes gave a very quantitative target, for physicists trying to understand the quantum nature of gravity, to aim for: come up with a complete and mathematically consistent theory which can microscopically account for the Bekenstein—Hawking entropy of black holes. This 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 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.

Quantum theory and Einstein gravity

As we have discussed earlier, the inevitability of focusing singularities that indicate a break—down 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 both 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 accounting of the black hole entropy without such a microscopic quantum description of gravity. The program to quantize gravity using the Einstein—Hilbert action as a starting point began in the early 1960s [2] and references therein. Just 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 $\frac{E}{E_{pl}}$, where E is the typical energy of the gravitons and $E_{pl} = \left(\frac{\hbar c^5}{G_N}\right)^{\frac{1}{2}} \sim 10^{19}$ GeV. This says that at energies $E \sim E_{pl}$ or equivalently time intervals $\delta t_{pl} \sim 10^{48}\, secs$, 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 $1/r$ 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 the extensive, volume dependence) of the black hole entropy on its size (as measured by the extent of 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 (1) is valid at $E \sim E_{pl}$ and whose low energy ($\frac{E}{E_{pl}} \ll 1$) limit is Einstein's theory and (2) is 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 in the sense we explain below. 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 sheds considerable light on Hawking's results.

Thus we will not describe the string theory answer to the first question but concentrate instead on the second question[4].

String Theory Microstates, Black Hole Entropy and Hawking Radiation

In order to see how string theory addresses this question 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 Boltzmanns formula $S = k_B \log \Omega$ where Ω stands for 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 Boltzmanns 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 generalised electric/magnetic charges, and of spatial dimension between 0 (points) and 9, labelled by p. These domain walls are the end points 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 appear 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 but 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 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 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 by 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, Curt 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 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. 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 a plethora of such solutions for which the Strominger—Vafa calculation has been generalised to with amazing success. It is also important to note that is 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 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 (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. Thus 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 (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 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 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 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. [3, 4]

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 quantum 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.

• 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 in—falling wave. In the boundary field theory this generalises 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,

$$\frac{\eta}{s} = \frac{\sigma_{abs}}{16\pi G_N s} = \frac{A}{16\pi G_N s} = \frac{\hbar}{4\pi k_B} \quad (4)$$

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 to show the positivity of the entropy current in uid dynamics[7].

• A formula for quantum entanglement entropy of a region A in a strongly coupled field theory was proposed by the Ryu—Takayanagi,

$$S_A = \frac{Area\ (\gamma_A)}{4\hbar G_N} \quad (5)$$

where *Area(A)* is the minimum area surface (co—dimension two) A in AdS space—time, whose boundary is the same as that of the region A. Even though the form is superficially that 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[8].

• Black holes scramble information most efficiently. In the quantum field theory this corresponds to the '*buttery effect*' that describes how a small disturbance in the far past spreads through the system characterised 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,

$$\lambda = \mathcal{K} \quad (6)$$

where $\mathcal{K} = 2\pi k_B T$ is the surface gravity and T is the temperature of the black hole. This inspired the proof that $\mathcal{K} = 2\pi k_B T$ is the maximum value ('chaos bound') of such an exponent in a unitary quantum system [9]. An example of a 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 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 59th 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 Mumbai did 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 Shanmukhananda Hall in north Mumbai 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* and subsequent popular science works and public engagements, Hawking was able to create a worldwide connect with the cosmic questions that physicists wrestle with. His book sold more than ten 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 co—authored 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 him the universally recognisable 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.

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All images are from Stephen Hawking's visit to India in 2001, courtesy of Tata Institute of Fundamental Research (TIFR), Mumbai.

PROGRAMS

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

Third Bangalore School on Population Genetics and Evolution
5—17 March 2018 ✦ *Organizers* — Deepa Agashe and Kavita Jain

Nonperturbative and Numerical Approaches to Quantum Gravity, String Theory and Holography
27 January—3 February 2018 ✦ *Organizers* — Poul H. Damgaard, Masanori Hanada, Anosh Joseph, Loganayagam R, Aninda Sinha and Toby Wiseman

Kavli Asian Winter School (KAWS) on Strings, Particles and Cosmology 2018
8—18 January 2018 ✦ *Organizers* — Minxin Huang, Sangmin Lee, Sungjay Lee, Loganayagam R, Suvrat Raju, Tadashi Takayanagi, Masahito Yamazaki and Gang Yang

J—Holomorphic Curves and Gromov—Witten Invariants
25 December 2017—4 January 2018 ✦ *Organizers* — Somnath Basu, Rukmini Dey and Ritwik Mukherjee

Winter School on Quantitative Systems Biology
4—22 December 2017 ✦ *Organizers* — Sidhartha Goyal, Kavita Jain, Vijaykumar Krishnamurthy, Luca Peliti and Mukund Thattai

Geometry, Groups and Dynamics (GGD) — 2017
6—24 November 2017 ✦ *Organizers* — C. S. Aravinda, Shrikrishna Dani, Krishnendu Gongopadhyay and Athanase Papadopoulos

DISCUSSION MEETINGS

Pressing for Progress — A Discussion Meeting on the Gender Gap in Physics
22 March 2018 ✦ *Organizer* — Prajval Shastri

Analytic and Algebraic Geometry
19—24 March 2018 ✦ *Organizers* — Indranil Biswas and A. J. Parameswaran

Indian Statistical Physics Community Meeting 2018
16—18 February 2018 ✦ *Organizers* — Ranjini Bandyopadhyay, Abhishek Dhar, Kavita Jain, Rahul Pandit, Sanjib Sabhapandit, Samriddhi Sankar Ray and Prerna Sharma

Turbulence from Angstroms to Light Years
20 January 2018 to 25 January 2018 ✦ *Organizers* — Rama Govindarajan and Shravan Hanasoge

ICTS at Ten
4—6 January 2018 ✦ *Organizers* — Rajesh Gopakumar and Spenta R. Wadia

Algorithms and Optimization
2—3 January 2018 ✦ *Organizers* — Prateek Jain and Nisheeth K. Vishnoi

Statistical Physics Methods in Machine Learning
26—30 December 2017 ✦ *Organizers* — Mikhail Belkin, Chandan Dasgupta, Partha Mitra and Rina Panigrahy

Consultation on National Education Policy (NEP) 2017
2 December 2017 ✦ *Organizers* — Manjul Bhargava, Leena Chandran-Wadia and Spenta R. Wadia

Surface Group Representations and Geometric Structures
27—30 November 2017 ✦ *Organizers* — Siddhartha Gadgil, Krishnendu Gongopadhyay, Subhojoy Gupta and Mahan Mj

Collective Dynamics of—, on— and around Filaments in Living Cells — Motors, MAPs, TIPs and Tracks
28 October—2 November 2017 ✦ *Organizers* — Tanweer Hussain, Ambarish Kunwar 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 Rainey *(Department of Microbial Population Biology, Max Planck Institute for Evolutionary Biology, Plön, Germany; Laboratoire de Génétique de l'Evolution, ESPCI 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)*

S. Chandrasekhar's fluid dynamics
22 January 2018 ✦ *Speaker* — Katepalli Raju Sreenivasan *(Dean of NYU Tandon School of Engineering; The Eugene Kleiner Professor for Innovation in Mechanical Engineering; Professor of Physics (Faculty of Arts and Science); Mathematics (Courant Institute of Mathematical Sciences))*

Symmetries, Duality, and the Unity of Physics
8 January 2018 ✦ *Speaker* — Nathan Seiberg *(Institute for Advanced Study, School of Natural Sciences, Princeton, New Jersey, USA)*

INFOSYS—ICTS DISTINGUISHED LECTURES

Mysteries Of The Higgs Boson
17 April 2018 ✦ *Speaker* — Michael E. Peskin *(SLAC, Stanford University)*

Symmetry in Quantum Gravity
15 January 2018 ✦ *Speaker* — Hirosi 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 Fisher *(Stanford University)*

The Science of the Man from the 9 Dimensions
14 January 2018 ✦ *Speaker* — Hirosi 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* — Robbert Dijkgraaf *(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
20 February 2018 ✦ *Speaker* — Rana 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

VISHVESHWARA LECTURES

ICTS has introduced a new lecture series, celebrating the life and work of C.V. Vishveshwara – a pioneer in black hole physics and science outreach in India. The Vishveshwara 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
11 January 2018 ✦ *Speaker* — Kip S Thorne *(Feynman Professor of Theoretical Physics at Caltech)*
Kip Thorne won the 2017 Nobel Prize for Physics.

KAAPI WITH KURIOSITY

Endless Forms Most Beautiful
25 March 2018 ✦ *Speaker* — Shannon Olsson *(National Centre for Biological Sciences (NCBS), TIFR)* ✦ *Venue* — J. N. Planetarium, Bangalore

Fascinating world of photons, superposition and entanglement
25 February 2018 ✦ *Speaker* — Urbasi Sinha *(Quantum Information and Computing (QuIC) laboratory at Raman Research Institute, 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

Paleovirology — the modern legacy of ancient viruses
10 December 2017 ✦ Speaker — Harmit 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

“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

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