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INTERNATIONAL CENTRE *for* THEORETICAL SCIENCES
TATA INSTITUTE OF FUNDAMENTAL RESEARCH

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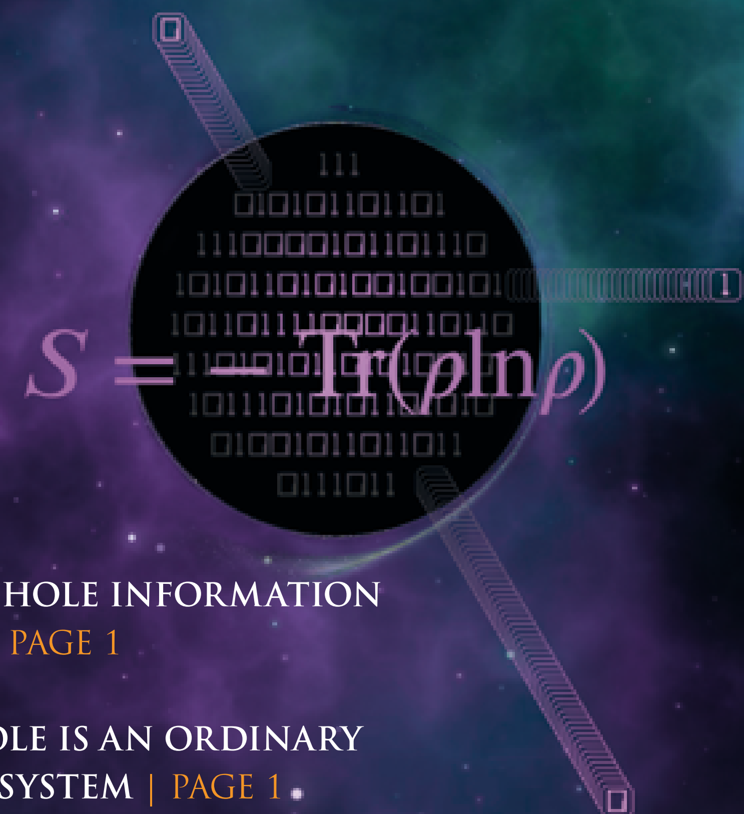

Editor- ANANYA DASGUPTA • Design - JUNY K. WILFRED

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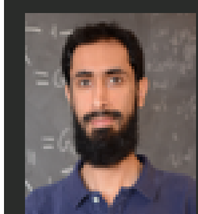
THE BLACK HOLE INFORMATION PARADOX

AHMED ALMHEIRI



During the last quarter of the 20th century, Stephen Hawking made a discovery that shook the very foundations of theoretical physics. In an attempt to understand the quantum nature of gravity, he showed that a sprinkling of the quantum on top of spacetime further complicates general relativity's most convoluted objects. Black holes, he argued, are no longer the eternal sinks of spacetime devouring whatever they might encounter, but instead they gradually shrink into nothingness while taking with them everything they've consumed, leaving behind a cloud of featureless radiation. Information, whose preservation is at the heart of physics, has been lost.

Hawking arrived at his result by using a theoretical physicist's oldest trick; he conducted a *gendanken* — German for 'thought'— experiment. This is the theoretical exercise of pushing a physical theory to its extreme by tweezing out predictions of carefully crafted physical scenarios. The hypothetical scenario is first represented as a set of equations which are then solved to reveal the predicted experimental outcomes. What makes Hawking's result paradoxical is that the bizarre conclusion (information loss) results from a well-established theoretical framework with mild assumptions and approximations; every step along the argument is robust, but the outcome is contradictory — it almost feels like a sleight of hand, without any visible tricks even under ...

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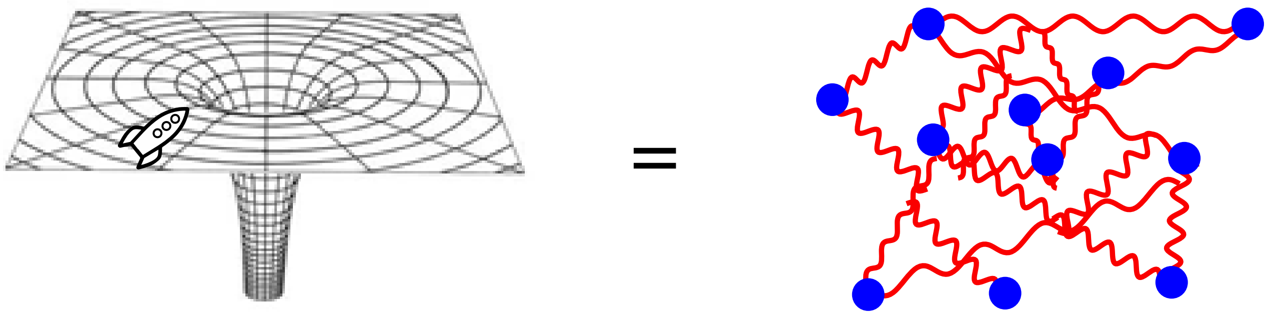
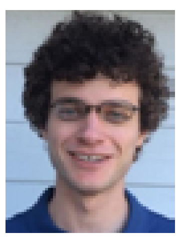


Fig. 1: A powerful idea in theoretical physics is the conjecture that a black hole (left) is secretly an ordinary quantum system (right).

A BLACK HOLE IS AN ORDINARY QUANTUM SYSTEM

DOUGLAS STANFORD



For nearly fifty years, high-energy theoretical physicists have been gradually sharpening an amazing conjecture, which can be summarized in one line:

A black hole is an ordinary quantum system.

This has been supported by the fact that black holes have a temperature and an entropy, and that they exhibit thermalization, chaos, and transport phenomena. In principle they can even be used to perform quantum teleportation.

The extraordinary power of the conjecture comes from the fact that it is not obviously true. Over the years, it has survived close calls, and the theory of black holes has had to show real ingenuity in order to satisfy the expectations of a quantum system. To prove it wrong, one would try to find some general property of quantum systems, and to show that it is not true for a black hole. In 1976, in the very early days of this conjecture, Hawking proposed a problem of exactly this type. He argued that when a black hole evaporates, it destroys the information originally contained in whatever formed the black hole. This irreversible destruction of information is forbidden in quantum mechanics, and Hawking's puzzle has become known as the "black hole information paradox."

There has been recent progress on resolving this problem, based on tools that were built incrementally over the last fifteen years,[1] and put together recently in independent papers by Penington, and by Almheiri, Engelhardt, Marolf, and Maxfield.

The central character in the story is the *entropy* of the Hawking radiation produced by a black hole during its evaporation. One version of entropy might be familiar from thermodynamics or statistical mechanics. That version (the "coarse-grained entropy") is defined as the logarithm of the number of states that are consistent with a very rough description of some system. For example, we could specify the energy and number of particles in a box of gas, and count the number of states that are possible given these constraints. This will be some huge number, and its logarithm is the coarse-grained entropy of the gas.

In quantum mechanics, there is another concept of entropy, known as the "fine-grained entropy" (or the "von Neumann entropy" or the "entanglement entropy"). This is a fundamental property of a quantum system which expresses the degree to which its state is unknown due to entanglement with another system.

... continued on Page 2 ...

EDITOR'S NOTE

Over the last couple of years there has been striking progress towards understanding the so-called 'Black Hole Information Paradox', the apparent violation of the rules of quantum mechanics in black hole backgrounds that Hawking first drew attention to 45 years ago. The new work on this long standing puzzle is reviewed here from the perspective of theoretical physicists, Ahmed Almheiri from IAS Princeton and Douglas Stanford from Stanford University.

Those interested in further reading can also look at 'The entropy of Hawking radiation', Ahmed Almheiri et al, e-Print: 2006.06872 [hep-th] for technical details. For a more general review one can read 'Recent Progress on the Black Hole Information Paradox: Computation of the Page Curve' by Raghu Mahajan, Resonance – Journal of Science Education Volume 26 Issue 1.

Also in this issue, senior astrophysicist Mayank Vahia writes about the ancient world and ancient astronomy. MB Rajani gives us an interesting geospatial analysis to study and preserve cultural heritage landscapes.

BETWEEN THE SCIENCE

SUBHRO BHATTACHARJEE's publication, with Adhip Agarwala, Johannes Knolle and Roderich Moessner, titled *Gapless State of Interacting Majorana Fermions in a Strain-Induced Landau Level*, was selected as Editor's Suggestion in Physical Review B.

MANAS KULKARNI and **ABHISHODH PRAKASH**'s, work (with J.H. Pixley) titled, *Universal Spectral Form Factor for Many-Body Localization*, was highlighted as Editor's Suggestion in Physical Review Research (Letter)

ANUPAM KUNDU and **PRASHANT SINGH's** publication titled *Local Time for Run and Tumble Particle* was selected as Editor's Suggestion in Physical Review E.

MANAS KULKARNI and his collaborator from Rutgers University, Jedediah Pixley was selected for a Rutgers Global International Collaborative Research Grant.

Stanford | *continued from Page 1 ...*

This is best explained with an example. Consider a quantum particle with a spin that can point either up or down, ↑ or ↓. If we have two such particles and they are both pointing the same direction, then we could imagine the states ↑↑ and ↓↓. In quantum mechanics, it is possible to consider a *quantum superposition* of both states

$$|\uparrow\uparrow> + |\downarrow\downarrow>$$

This is a completely definite state of the combined system, and we say that its fine-grained entropy is zero. However, it has the property that the state of either one of the particles by themselves is not definite; it could be ↑ or it could be ↓. There are two possible states, so the fine-grained entropy of either particle individually is the logarithm of two: $S = \log(2)$.

The puzzle from 1976 has to do with fine-grained entropy of *Hawking radiation*. Hawking showed that black holes slowly radiate energy, and if left alone, they will gradually "evaporate" and disappear altogether, a bit like a slowly burning piece of coal.

What is the fine-grained entropy of the Hawking radiation? It is convenient to imagine the black hole (BH) started out in a completely definite state, so that its fine-grained entropy was zero. In quantum mechanics, the future state of a complete system is determined uniquely by the past state. So if the BH plays by the rules of quantum mechanics, the complete system (BH + radiation) must remain in a definite state for all time, with zero entropy. In particular, this implies that at the end of evaporation, when the BH is gone and only the radiation remains, the radiation must have zero fine-grained entropy. This is a simple but powerful prediction of the conjecture that a black hole is an ordinary quantum system.

Now – finally – we can state the puzzle. A simple calculation shows that in fact, the finegrained entropy of the radiation is nonzero, and in fact it increases steadily over the lifetime of the black hole. So in particular, it does not end up equal to zero, contradicting our prediction above. Less abstractly, the implication of this is that even if the BH starts out in a definite state, its final form (the radiation) will not have a definite state, so the future will be unpredictable. This "breakdown of predictivity" is a clear violation of the rules of quantum mechanics.

It has long been suspected that there must be some mistake in the simple calculation that led to this conclusion, but it wasn't clear what the mistake was. Essentially, the recent progress identified a mistake, and showed that after correcting it, the entropy of Hawking radiation ends up being zero. Even better, its detailed dependence on time agrees precisely with expectations from quantum mechanics (as set out by Page in 1993).

To understand the correction, we need a little more detail about how the entropy is computed. The mathematical formula for the von Neumann entropy (S) is

$$S = -\operatorname{Tr}(\rho \log(\rho))$$

Here ρ is a matrix (the density matrix) that describes the radiation. Because the matrix logarithm in this formula is sometimes difficult to work with, it is sometimes convenient to use an equivalent formula

$$S = -\lim_{n\to 1} \frac{1}{n-1} \log \operatorname{Tr}(\rho^n)$$

If we imagine that n is taken to be some integer 2, 3, 4, ... , the right-hand-side doesn't contain any matrix logarithms. Instead, it involves an integer number of copies of the matrix ρ, all multiplied together. If you can compute this function accurately for integer values of n, then it is often possible to compute the limit as n approaches one and recover S.

This mathematical device is known as the "replica trick" because for integer n, the expression on the right-hand-side involves n "replicas" of the density matrix ρ. Physically, these replicas correspond to n different copies of the Hawking radiation system, each connected to a corresponding black hole. In a naive calculation of the entropy of the Hawking radiation, each of these n black holes are taken to be independent and unrelated copies. However, a more general possibility is to allow the black holes to be connected by spacetime configurations called wormholes. After allowing this possibility, it turns out that one gets the right answer for the entropy, consistent with quantum mechanics. In other words, the "mistake" that led to the contradiction with quantum mechanics was to neglect the possibility of wormholes connecting together the different replicas.

One could object that these replicas are unphysical: a mathematical trick introduced at an intermediate step in order to finesse the logarithm. In the limit n→1, we only have one replica, so how can it connect by a wormhole to any other replicas? In fact, the wormhole connection for n > 1 has an avatar at n = 1, which is roughly the location at which the replicas *would* connect together if there were more than one of them. This location is known as the "quantum extremal surface," and it is a physical location in the spacetime geometry. This surface was identified directly in the papers by Almheiri, Engelhardt, Marolf, Maxfield, and Penington. For the case of an evaporating black hole, it is close to the event horizon, and the details of its size and location agree precisely with the demands of quantum mechanics.

So where does that leave the conjecture that black holes are ordinary quantum systems? Once again, it appears to have survived by the skin of its teeth, teaching us new lessons about spacetime, wormholes, and entropy in the process. □

Footnote

1. By Ryu, Takayanagi, Hubeny, Rangamani, Lewkowycz, Maldacena, Faulkner, Dong, Engelhardt, and Wall.

Douglas Stanford is a theoretical physicist. He is professor of physics at Stanford Institute for Theoretical Physics of Stanford University, USA.

Almheiri | *continued from Page 1 ...*

closer inspection. This indicates a deficiency in the established physical theory, or our understanding of it, and holds promise of a major new physical insight right around the corner.

The story of black holes is filled with a healthy mix of confusion and insight. It took a little under 60 years for physicists to realize that there was more to them than weirdly configured patches of spacetime. A paradigm shift came at the hands of Jacob Bekenstein who uncovered surprising implications of classical thermodynamics on black holes. His insights came from considering the thought experiment of lowering matter with entropy into a black hole. Two things would happen from the perspective of an observer outside the black hole: the total thermodynamic entropy of the outside universe will appear to decrease, while the size of the black hole — the area of its event horizon — will increase due to the growth of its mass since its radius is proportional to its mass

$$\text{Horizon Radius} = 2G_N M/c^2$$

where G_N is Newton's gravitational constant, c is the speed of light, and M is the mass of the black hole. The first observation is problematic as it implies a violation of the second law of thermodynamics which demands that entropy can only increase or stay the same. However, the second law can be saved once the area of the horizon is interpreted as a contribution to the total thermodynamic entropy of the universe, generalizing the notion of entropy to a 'generalized entropy'

$$S_{gen} = \frac{\text{Horizon area}}{4G_N} + S_{outside}$$

The symbol S stands for entropy. The second law would be respected if the area increase is larger than the outside entropy decrease as matter is lowered into the black hole. The area contribution to the generalized entropy can be thought of as the thermodynamic entropy of the black hole, and is known as the Bekenstein-Hawking entropy, given more precisely by

$$S_{BH} = \frac{c^3 k_B}{4G_N \hbar} \times \text{Horizon area}$$

This is a tantalizing formula unifying all the fundamental constants from many different areas of physics; c for the speed of light from special relativity, k_B for Boltzmann's constant from statistical mechanics, $\hbar$ for Planck's constant from quantum mechanics, G_N for Newton's gravitational constant from general relativity, (and π for circles!).

The thermodynamic entropy in ordinary systems has a statistical interpretation of measuring the total number of possible configurations of a system, or simply its microstates, and the Bekenstein-Hawking entropy begs the question of what those might be for a black hole. The number of microstates is equal to the exponential of the entropy

$$\operatorname{Exp}[S_{BH}/k_B]$$

A quick calculation shows that new physics is essential to account for all of these microstates. We could compare the entropy of a black hole of mass M to that of black-body radiation at the same energy, namely Mc^2, contained in a sphere with the Schwarzschild radius whose volume is $4/3\pi\,(r_H)^3$. For a solar mass black hole, the ratio of those two numbers is

$$\frac{\operatorname{Exp}[S_{\text{Black body}}/k_B]}{\operatorname{Exp}[S_{BH}/k_B]} = \frac{\operatorname{Exp}\left[\frac{4}{3}\left(\frac{V\pi^2}{15c^3\hbar}\right)^{1/4} E^{3/4}\right]}{\operatorname{Exp}\left[\frac{c^3}{4G_N\hbar} \times \left(\frac{\pi\, 2G_N M}{c^2}\right)^2\right]} \approx \frac{1}{10^{10^{77}}}$$

The entropy of the radiation is completely dwarfed by that of the black hole. Filling in the gap between these two numbers remains an important open problem in quantum gravity. Some success in doing so has been achieved in special settings in string theory, our leading theory of quantum gravity, where these extra microstates are configurations of extended objects called D-branes.

Up to this point, we saw that a black hole, as seen from the outside, shares some features with ordinary systems, namely an energy and entropy. The question is how far does this analogy go? Well, ordinary systems are intrinsically quantum, so what does a quantum black hole look like? The strength of quantum effects of spacetime are controlled by the gravitational coupling constant, which is a synthesis of all the fundamental constants, combined with the largest energy scale in the physical scenario, giving

$$\text{Gravitational Coupling} \sim \frac{4G_N\hbar}{k_B c^3}\left(\frac{c^4}{2G_N E}\right)$$

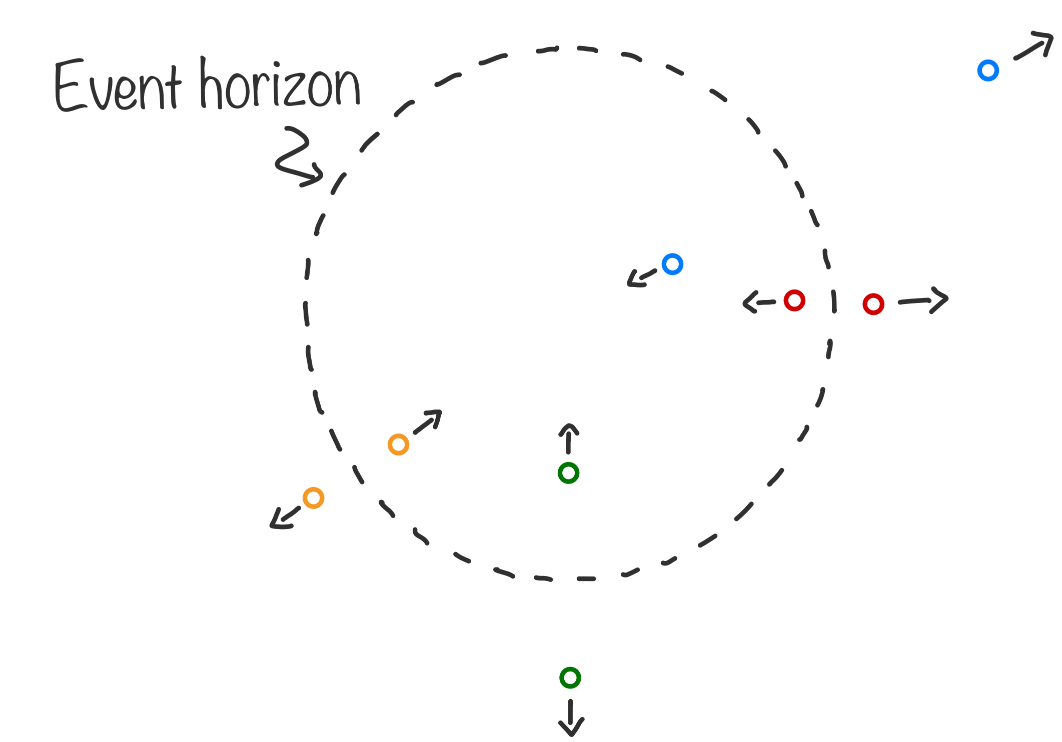
The strength of these quantum effects are proportional to the inverse of the Bekenstein-Hawking entropy of a black hole of energy E. Therefore, when studying a large black hole, this is an astronomically small number compared to, say, the coupling constants appearing in the standard model of particle physics.

While quantum effects of spacetime might not be significant, quantum effects of matter propagating on this spacetime are. What is normally done is to work in a so-called semi-classical approximation, where quantum matter interacts with a classical spacetime. Einstein's equations in this approximation govern the warping of spacetime due to a quantum mechanical average of the matter energy,

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G_N}{c^4} \langle T_{\mu\nu} \rangle$$

The right hand side of this equation is sometimes called the expectation value of the stress energy tensor, and it sources the curvature of spacetime on the left hand side.

The behavior of quantum matter in the presence of an event horizon leads to black hole evaporation. The physical mechanism for this is rather simple, and relies on an intrinsically quantum property known as *quantum entanglement*. In quantum field theory, the emptiness of space is ensured by a sea of pair-wise entangled particles. These pairs usually remain side-by-side and move together. The novelty introduced by black holes is that a pair could be on either side of the event horizon, which ultimately separates them from one another; the inside particle crashes into the singularity while its outside partner flies away from the black hole. The outside particle carries positive energy away from the black hole, while the interior particle has negative energy, as required by energy conservation, and thus reduces the total mass of the



black hole. An external observer hovering nearby the black hole would witness the black hole slowly shrinking and measure a flux of positive energy, a temperature, emanating from the black hole. This outgoing radiation comprises what is known as the Hawking radiation of the black hole.

This quantum entanglement is the very same concept that tormented Einstein, but it now makes an appearance in a gravitational setting. Entanglement is the quantum phenomenon that allows two systems to be correlated in a way not achievable in ordinary classical physics. In particular, entanglement can ensure that any measurement outcome on one system is perfectly correlated with a corresponding measurement on the other. An example of two entangled systems is two dice in the quantum superposition of being both 1's, 2's, up to 6's, often written as 1,1 + 2,2 + 3,3 + 4,4 + 5,5 + 6,6. If one dice was measured and found to be 3, say, then the other dice is determined to also be 3, and similarly for the other possibilities.

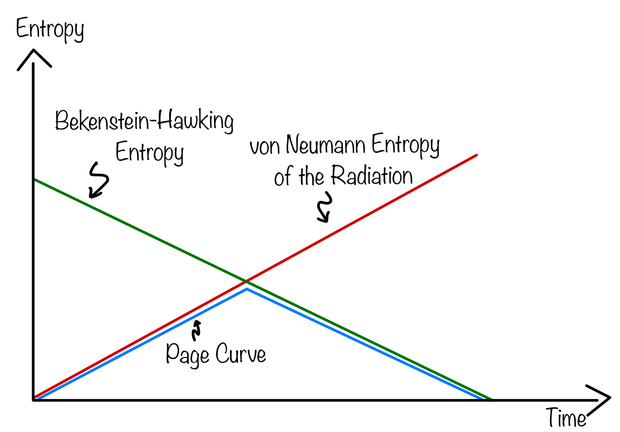
The degree of entanglement between two systems is quantified by the number of correlated measurement results between them. The logarithm of this number is known as the von Neumann entropy of each system, or simply the entanglement entropy between them. There were 6 correlated possibilities for the pair of dice, and hence the von Neumann entropy of each dice is Log[6]. It follows straightforwardly that the largest the von Neumann entropy can be, is the logarithm of the total number of states of the system, and therefore the two dice in the above example are maximally entangled. An example where they are not maximally entangled is the quantum state 1,1 + 2,2; the two dice have zero probability to be found in 3 - 6, but are nevertheless entangled in a smaller subspace of possible results, each with a von Neumann entropy of Log[2]. A state with no entanglement is 1,1, with zero entropy.

Entangling a system with something else reduces the total number of measurements that have a priori definite results. Since the amount of information one has can be quantified as the number of measurements that they can predict with certainty, it is negatively correlated with the amount of von Neumann entropy. For the dice examples above, the case of 1,1 has 6 predictable measurements on the first dice (100% for 1, 0% for 2 - 6), four for 1,1 + 2,2, and zero for 1,1 + 2,2 + 3,3 + 4,4 + 5,5 + 6,6. Therefore a system that is maximally entangled with something else can be said to contain no information.

The entangled particle pairs across the event horizon of a black hole are similar to the pairs of maximally entangled dice. Every emitted Hawking particle leads to a growth in the entanglement between the Hawking radiation and the inside of the black hole. The process continues until the mass of the black hole reaches the Planck mass, at which the gravitational coupling constant becomes large and spacetime quantum effects become important.

During this late stage of black hole evaporation, the semi-classical approximation is unjustified and Hawking's analysis breaks down. Nevertheless, a problem arises way before this breakdown.

The tension starts once the von Neumann entropy of the black hole becomes comparable to its thermodynamic entropy. The thermodynamic entropy, which is a measure of the number of black hole microstates, decreases with time as the black hole shrinks being proportional to the area of its event horizon. The von Neumann entropy, however, starts at zero and increases monotonically for the entirety of the evaporation process. Roughly half way through, the two entropies cross and the von Neumann entropy of the radiation exceeds the thermodynamic entropy of the black hole. This is not a sensible result: the black hole simply doesn't have enough microstates, as measured by the Bekenstein-Hawking entropy, to support the excess von Neumann entropy.



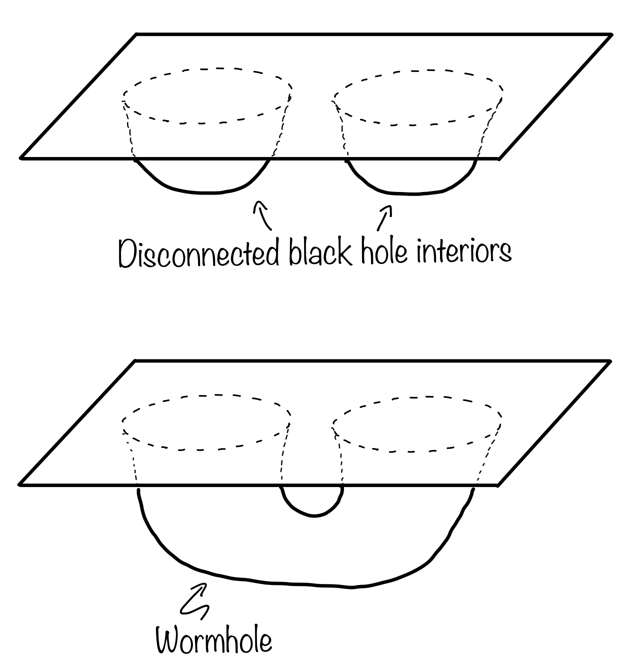
The problem becomes more glaring once the black hole completely evaporates away. What remains is the Hawking radiation with a large von Neumann entropy, implying a huge deficit of information. This would be true even if the black hole was formed from a star initially without any von Neumann entropy. The evaporation then destroys information by transforming a state with definite predictions to one without. Black hole evaporations lead to a loss of predictability.

This tension comprises the black hole information paradox, putting in jeopardy the idea that black holes, at least as viewed from the outside, behave as normal quantum mechanical systems. Normally, the von Neumann entropy cannot exceed the thermodynamic entropy, and so the entanglement between the black hole and the radiation should increase only until it saturates the Bekenstein-Hawking entropy of the black hole, after which it must follow the Bekenstein-Hawking entropy down to zero as the black hole shrinks. This sought-after evolution of the entropy is known as the Page curve, and reproducing it is a necessary condition for resolving the information paradox. However, this seems hopeless given the robustness of the semi-classical approximation for most of the black hole's lifetime. Indeed, small corrections to this approximation due to spacetime quantum effects have famously been ruled out by seminal work of Samir Mathur, professor at Ohio State University.

This conclusion can't be right. It would imply that quantum mechanics and gravity are simply incompatible, and that our universe is secretly not quantum mechanical!

Fortunately, a new set of results puts this inevitability to rest. The new strategy, implemented in a set of papers in 2019 (including work involving Raghu Mahajan, currently a postdoc at Stanford University) is to allow for possible quantum gravitational effects, even if they seemed small at first.

The surprise is that subtle but important effects do indeed kick in right when they are needed, once the radiation von Neumann entropy crosses the thermodynamic entropy, and invalidate the original semi-classical approximation. These effects aren't some crazy uncontrollable quantum fluctuation of spacetime, but rather involve the semi-classical approximation about a new spacetime altogether. Stated briefly, since the von Neumann entropy is sensitive to the number of measurement outcomes, it is calculated by considering many copies of the system and evaluating the probability of certain joint measurements on them. With multiple copies of the evaporating black hole, unshackling gravity allows for the generation of wormholes that connect their interiors together. Partly because of the measurement on the radiation and partly because of the large entanglement at the Page time, gravity maximizes the probability of the desired outcomes by generating the wormholes. It becomes overwhelmingly more likely to have the wormhole than not, and thus the correct semi-classical approximation becomes the one on top of the wormhole spacetime. The original semi-classical approximation precludes these wormholes by assumption. In technical terms, a first order phase transition has occurred between two saddle points of the gravitational path integral.



These wormholes induce a simple modification of the von Neumann entropy formula of the Hawking radiation for a single evaporating black hole. After the Page time, the entropy is given by a formula analogous to Bekenstein's generalized entropy, but with a twist.

$$S_{\upsilon N}^{\text{exact}} = \frac{\text{Island boundary area}}{4G_N} + S_{\upsilon N}(\text{Hawking Radiation+Island})$$

The modified von Neuman entropy of the Hawking radiation breaks up into two pieces. The first is the original semi-classical von Neumann entropy of the Hawking radiation but which now includes a region inside the black hole, known as the Island. The second piece is the area of the boundary of the Island, situated near the event horizon of the black hole.

The precise location of the Island depends on the amount of Hawking radiation that's been emitted. This formula is known as the Island formula.

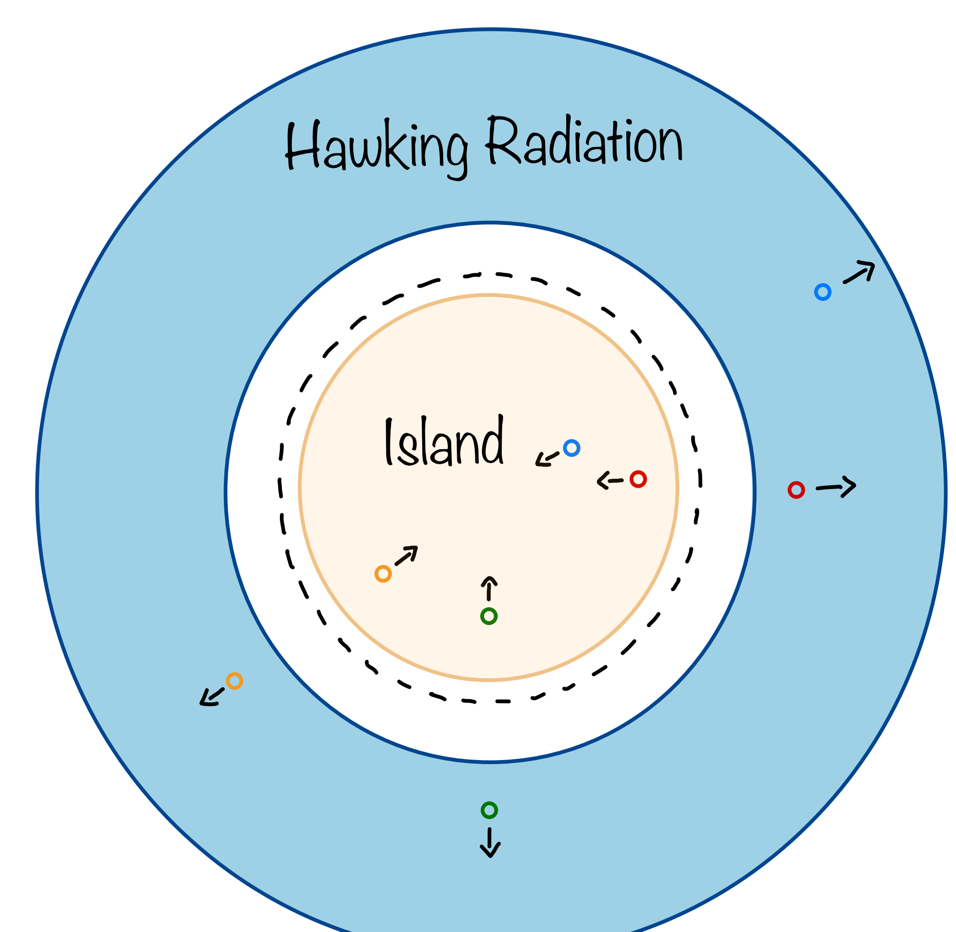
It's not too hard to see how this formula leads to a decreasing von Neumann entropy with time. First, recall that the original problem came from the von Neumann entropy of the outside Hawking particles growing due to their entanglement with their partners inside the black hole. In this new formula, however, the von Neumann entropy includes the Island which contains those interior partners, and hence the entanglement between the inside and outside is no longer counted. The dominant contribution to the modified von Neumann entropy of the Hawking radiation comes primarily from the area of the boundary of the Island, or essentially the area of the event horizon. This decreases with time as the black hole shrinks.

The Page curve is then obtained from the transition between the two semi-classical approximations, before and after the Page time, respectively, without and with the effects of the wormholes. The entropy as a function of time is compactly expressed as the minimum between these two formulas

$$\text{Minimum}\left\{S_{\upsilon N}(\text{Hawking Radiation}) \,\middle|\, S_{\upsilon N}^{\text{exact}}\right\}$$

The implications of the Island formula are astounding. The inclusion of the Island in the entropy calculation means that it is secretly encoded in the Hawking radiation faraway. Indeed, certain operations on the Hawking radiation have been shown to directly influence or probe the Island by generating a wormhole into the black hole interior. In this picture, dropping information into the black hole would in some sense have already escaped once it enters the Island. These results are a precise realization of previous conjectures on the possibility of a non-local identification between the black hole interior and the Hawking radiation as a means to address the information paradox, including seminal work involving Suvrat Raju, professor at ICTS.

As amazing as this result is, it doesn't solve everything about black holes. One thing it doesn't address is how to find the precise mapping between the possible initial states of the black hole and the final states of the Hawking radiation. In particular, it doesn't shed any light on the nature of what the black hole microstates are. Moreover, it doesn't inform us on the makeup of the black hole singularity either.



Nevertheless, it does restore the hope that a black hole, even at the quantum level, continues to behave as a normal quantum system when viewed from the outside. Namely, it behaves as if it has a finite number of microstates, it follows the Page curve, and information dropped into one can be recovered from the radiation. In this respect, it isn't that different from a burning piece of coal.

45 years after Hawking discovered the information paradox, we have a possible answer for the missing ingredient in his calculation, namely the spacetime wormholes. Yet, the journey has not concluded with many black hole mysteries that remain to be solved. This progress gives us a surge of confidence that we are on the right path. □

Ahmed Almheiri is a theoretical physicist. He is a Long-term Member at the Institute for Advanced Study, Princeton, USA.

ONLINE EXHIBITION

COSMIC ZOOM

As part of a major outreach initiative, ICTS launched a virtual exhibition titled **'COSMIC ZOOM.'** Based on the theme ***'Scales of the Universe'***, this exhibition and the associated online events were attended by more than 30,000 people.

The exhibition was targeted at a wide audience, from school children to university students. It took the visitor on a Cosmic journey, through the smallest to the largest scales in the Universe. The exhibition also hosted lectures, interactive sessions with labs and observatories, book readings, workshops for children, film screenings and conversations with researchers. The topics covered by these events include astronomy, particle physics, quantum information, cell biology, search for extraterrestrial life, toys and several others.

This outreach effort has been made successful by the efforts of a team of scientists, science communicators and designers from ICTS, with help from scientists across the country.

Cosmic Zoom was planned as a curtain-raiser for a proposed 'Bengaluru Science Habba' - a science festival conceived by a consortium of academic research institutions in Bengaluru.

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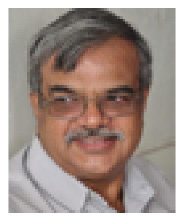
ANCIENT WORLDS AND ANCIENT ASTRONOMY

MAYANK VAHIA



It must have been a strange experience for the person who first noticed the stars. It was a leap of observations that needed the brains of at least a Homo Erectus if not Homo Sapiens. The third dimension of heavens is not easy to comprehend. As far as we know, only the humans are aware of its existence in an active way. ...

The brain of animals is not designed to comprehend it simply because it is of no relevance in this great quest of life to eat, not be eaten and to reproduce. It required the surplus brain power – over the needs to keep the body in check – to look around and see other things. Only mice, men and dolphins can claim to have brains that are larger than those that bodies require (Fig. 1). Even amongst the Homo series of animals, only Chimpanzees have a small excess of computing power and are hence are socially better organised. But just the size of the brain is not sufficient to point to this comprehension of the strange entity called the sky.

Even one of our nearest cousins, the Neanderthals had a brain of roughly the same sizer as early humans (1500 cc) and bigger than that of modern humans (1300 cc), humans had slightly larger frontal lobes. That brain region controls decision-making, social behavior, and such uniquely human tendencies as creativity and abstract thought. Humans had better technology. Good cognitive capacity allowed the rapid spread of new technologies, as well as

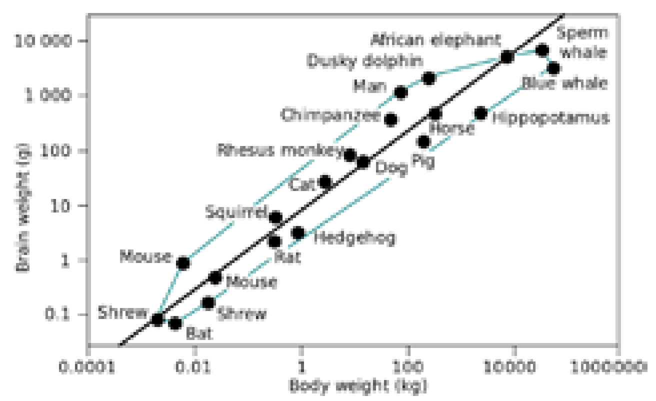


Fig. 1: Graph showing brain size of animals according to bodyweight.

the sharing of knowledge and information relevant for survival. This is probably the reason why only the Homo Sapiens know about the sky. And the realisation is relatively new. The oldest recorded astronomical sky is some fifteen thousand years ago in the Lascaux caves in France. Other studies also suggest similar time scales of our use of sky to track the year.

However, once the idea of the dimension of sky arrived amongst the human race, everything changed. Astronomy pervaded a whole host of human activities. The first thing one would notice is that the Earth becomes fertile only when it rains. As an analogy to humans therefore, Earth becomes Mother and the skies are where the Father lives when he seeds the Earth, new life comes.

Fig. 2: Stone observatory in Nilaskal near Udupi. (PHOTO CREDIT: Srikumar Menon)

Welcome to the first religion – and there are some who believe that even the Neanderthals probably harboured some such beliefs – based on how their graves were organised. The drama of thunder, lightening and other bad tempered events happening in the sky, would have only reinforced these ideas.

The Sun would have been noticed as the giver of warmth – something many animals do, and some lizards even warm themselves in the Sun in the morning before beginning their day. This is something even nomadic humans would have noticed.

But humans note more, they note the location from which the Sun rises. And it only rises in general in the East and sets in the West. But within this, the direction of rise in locations that go from North East to South East. In the northern hemisphere, as soon as the Sun rises, it moves South. As a result, if it is in the south and moving further south, its trajectory does not keep it in the sky for long. But farther north is the Sunrise point the longer does the Sun remain in the sky, but the days are also warmer (and longer if you wish, but this is not easy realise). So the Sunrise point defines the warmth and seasons. In the region affected by the monsoon of the Indian Ocean – the entire region from South East Asia to Eastern Africa – the humans would notice that the Sun reaching the northern most point also brings in Monsoon. This would be important for farmers and the first farming brings up stone observatories such as the one in Nilaskal near Udupi where huge stones are so arranged that only on special days (solstices and equinoxes), would shadows from one stone touch another one several meters away and the sun's beam would be collimated in a particular manner (Fig. 2, courtesy Srikumar Menon)

Moon would also have fascinated the humans. Its vexing and waning would have certainly fascinated humans.

Very soon humans must have noticed its strict periodicity and the relation between arrival of some patterns in the sky with seasons. They would also have noticed that the location of the point of sunrise is associated with a specific pattern of the sky appearing from that location. More interestingly, they would notice that 12 full (new) moons brought the Sun approximately back to where it was and the seasons began anew. The 12 months of the year were born. This would be of great importance to farmers but if you agree with Tilak's writing in his book Orion, even nomads who entered India some 4000 years ago, had these patterns in mind and their memory went back to some 10,000-year-old sky patterns!

This was a breakthrough that would not arrive until seasons became important to humans. Astronomy must have become important to settled cultures as that would be their (almost) sole obsession in the nights. So a whole host of lovers of astronomy emerge. Lovers of astronomy include

o Artists
o Farmers
o Travellers
o Calendar makers
o Priests
o Astronomers

These would be joined by astrologers and soothsayers later on, as the society became wealthy and were anxious about their and their children's future and their desire to take undertake important events on 'auspicious' times.

From here on, for several millennia, the observation of the Sun, Moon, seasons, shadows and occasional shooting stars and comets would be matter of curiosity and various philosophical speculations and evolution of ideas of religion. It would pervade all major human activities – farming, religion, architecture (of temples at least) and literature.

In fact, one can map the growth of astronomy to growth of civilisation in 4 major phase transitions:

1. Initial steps where humans would note the relation between sunrise and seasons. This phase would last between 30,000 BC to about 10,000 BC (8,000 YBP)

2. Settlement Astronomy where humans would the location of Sunrise in terms of geographical markings and astronomical patterns, and track seasons and marking of stars for astronomy. In the context of the Indian subcontinent, this phase would be 5,000 to 2,500 BC for Harappans and up to 1,500 BC or later for Vedic and other cultures.

3. Astronomy of civilisation when humans would develop of astrology and cosmogony, speculating about our place in the great scheme of things. They would also start building temples, which represents the cosmos on Earth. This phase would last from 2,500 to 1,900 BC for Indus Civilisation and 1,500 BC to 500 AD – Upanishad/ Purana period.

4. Technology based phase where state supported astronomy would start with using and developing mathematical tools to quantify astronomy and with the arrival of multi-wavelength, space based astronomy would give us our current understanding of astronomy. We would get modern astronomy with all its trappings. In the Indian subcontinent this starts with the arrival of Siddhantic Astronomy of Aryabhata in 500 AD but this would see a major boost with the arrival of telescopes etc. in the 18th century.

By knowing how sophisticated a culture's astronomical work is, it is possible to determine its general intellectual and socio-cultural level. In table 1 we quantify the astronomical knowledge of astronomy of various population groups based on their understanding of various facets of astronomy.

When we plot the astronomical knowledge of people with this period of settlement we end up with a graph shown in Fig. 3. Note that we have not included data from modern cultures as that would produce an exponential rise as expected.

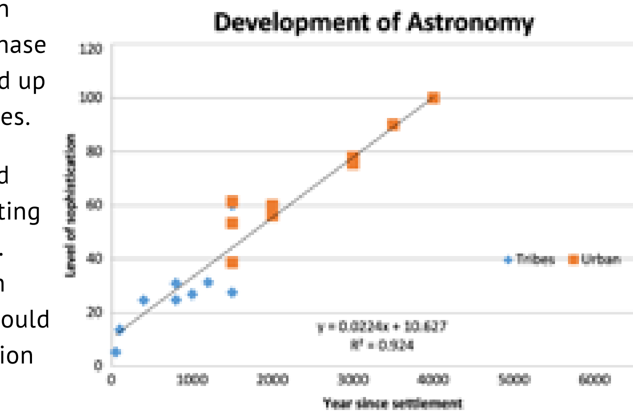


Fig. 3: Graph plotting astronomical knowledge with period of settlement.

The graph clearly demonstrates that the longer a culture is settled, the more sophisticated their astronomy. The correlation is so strong, that one can infer the period of settlement of a civilisation based on its astronomy or estimate the sophistication of astronomy based on their period of settlement. □

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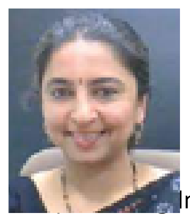
	Community	Period since settlement	Level of Astronomy										Cumulative score
			Name for directions	Know constellations: <5=0.3;5-10=0.6 ; >10=1	Astronomy in daily life	Myths of seasons	Philosophical myths	Astrology	Eclipses	Planets	Lunar mansions	Observatories	All
1	Relative weight		1	10	5	8	10	10	10	10	10	10	
2	Gonds	1200	1	0.6	0.5	1	1				0.2		29.5
3	Korku	1000	1	0.6	0.2		0.5		0.4	0.5		0.2	24
4	Kolams	800	1	0.6	0.5	1		0.2	1				29.5
5	Pardhi	400	1	0.5	1			0.2	1	0.2		0.2	22.5
6	Banjaras	100	1	0.3		1							12
7	Warli	800	1	0.3	0.2		0.5		0.3		1		23
8	Cholannaikans	50	1	0.2	0.1				0.2				
9	Nicobar	1500	1	0.6	0.1	0.5	0.3		1	0.2			26.5
10	Sumerians	3000	1	1	0.5	1	1	1	1	1		0.5	66.5
11	Greeks	2000	1	0.3	0.5	1	1	1	1			0.5	49.5

GEOSPATIAL ANALYSIS TO STUDY AND PRESERVE CULTURAL HERITAGE LANDSCAPES

M. B. RAJANI



India's high population density coupled with the rapid development of towns, industries, and transportation networks places an immense premium on land. In this context, protecting India's rich built heritage is a huge challenge. The Archaeological Survey of India (ASI) is responsible for over 3,600 sites, including many of the 30 sites inscribed by UNESCO as World Heritage Sites and 42 that are in the Tentative List (properties intended to be nominated). Further, each State's Department of Archaeology is typically responsible for a few hundred sites. As per the provisions of the Ancient Monuments and Archaeological Sites and Remains (AMASR) Act (1952, amended in 2010), these agencies recommend which archaeological sites should be protected. The recommendation for a site is based on its authenticity and integrity. The policies proposed in this note seek to strengthen the ability of these agencies to protect the integrity of archaeological remains of our nation's past without stifling present and future development.

Background

As defined in the ASI's Draft Guidelines (2009) , the integrity of an archaeological site is "a measure of wholeness or intactness" of the site, including "all elements necessary to express its national importance from historical, artistic or archaeological points of view". Integrity is particularly relevant when a site consists of several historical structures spread over a region. While determining the integrity of a site, the ASI guidelines require assessing whether the remains are "safe enough or is already suffering from adverse effects of development and/or neglect." Thereafter, a suitable Protected Area is selected based on traditional exploration on-site and surveys of remains that are visible from the ground. Once the Protected Area is determined, the Act provides definitions of Prohibited and Regulated Areas, which respectively extend to 100 m and an additional 200 m in all directions from the Protected Area.

Issues

This article will discuss two key issues.

1. The need for leveraging a combination of historical data as well as satellite imagery and GIS technologies to identify the historical extent of the site, and thereby define/redefine more effective protection boundaries.
2. The need for establishing a National Archaeological Database (NAD) to serve two purposes:
   a. Effective monitoring of activities within the Protected, Prohibited, and Regulated Areas by multiple stakeholders (including local communities).
   b. Efficient planning for development projects while preserving archaeological remains to the extent possible.

QUESTION 1

Are there more effective ways of delineating protection boundaries to ensure site integrity?

For Nationally protected monuments, ASI's draft guidelines (2009) adopt several of the recommendations of UNESCO's World Heritage Convention (WHC). Among these is the use of satellite imagery and GIS to identify site protection boundaries. ASI presently leverages these technologies at sites where the Protected Area has previously been identified through traditional means. Specifically, the BHUVAN geoportal uses GIS to automatically extend the (digitized) Protected Area of each ASI site to 100 m (Prohibited Area) and 200m further (Regulated Area), forming two concentric annuli around the former.

However, these cost-efficient and non-invasive technologies, which complement traditional on-site surveys and exploration, have not been used to define the Protected Area at any UNESCO, ASI or State Department site in India. The WHC recognises that some countries lack economic, scientific, and technological resources to develop an effective and permanent system of protection in accordance with modern scientific methods. These challenges should not apply to India.

The Heritage Science and Society programme at NIAS has developed expertise in leveraging these technologies (together with historical/archaeological scholarship) to identify several unprotected archaeological structures that have been overlooked by on-ground studies. Often, these structures lie close to Protected Areas but have been unwittingly excluded. The recently published book *Patterns in Past Settlements: Geospatial Analysis of Imprints of Cultural Heritage on Landscapes* describes many instances of this phenomena. A case study based on our research at Nalanda is presented to demonstrate how better site integrity can be ensured by utilizing these technologies in defining the Protected Area.

QUESTION 2

Can spatial information pertaining to protection boundaries be made widely accessible?

For sites under ASI protection, an online decision support system named SMARAC has been created to efficiently process requests for clearances to develop nearby plots of land. Further, by making this spatial information publicly accessible, this valuable service enables other stakeholders (including members of the local community) to monitor the land use within the Protected, Prohibited, and Regulated Areas and report potential misuse to the authorities in a timely manner. Extending this service to sites outside ASI's protection, as well as to unprotected sites with potential or confirmed archaeological value will further strengthen the fragile integrity of built heritage, at least in their present state. To demonstrate this point, a case study of Bodhgaya (not an ASI site) is presented, where significant development has taken place, particularly since the site was inscribed as a World Heritage in 2002.

CASE STUDY 1: **Nalanda**

Nalanda has been protected by ASI from early 20th century, and it was recognized as a World Heritage site in 2016 . In preparation for such recognition, UNESCO's World Heritage Convention (WHC) necessitates marking so-called Core and Buffer zones. The WHC Operational Guidelines state that boundaries are drawn to include "all those areas and attributes which are a direct tangible expression of the Outstanding Universal Value of the property", as well as "those areas which in the light of future research possibilities offer potential to contribute to and enhance such understanding".

One of the factors that makes Nalanda outstanding is that it was the largest and longest serving (5th century CE to 13th century CE) monastic-cum-scholastic establishment in the Indian Subcontinent. At its peak, it accommodated thousands of scholars, and such numbers could not have been supported within the $0.23 km^2$ area that ASI presently protects. Thus, in seeking World Heritage status for Nalanda, there were strong reasons to define boundaries differently to the stipulations of the AMASR Act. However, as shown in Fig. 1a, the Core Zone corresponds precisely to the area ASI had previously identified as the Protected Area for the site, and the Buffer Zone falls largely within ASI's Regulated Area. The same is true at most other sites in India that have attained World Heritage status or are in the tentative list.

Using satellite imagery (Remote Sensing) and GIS technologies, we have identified a palaeochannel that drew water to the site, as well as a cluster of past and present water bodies whose shapes, proximity and pattern of spread suggests a more realistic historical extent of the Nalanda's establishment (Fig. 2a).

As long as these regions remain unprotected, we risk losing an opportunity to enhance our understanding of intangible heritage, such as the engineering skills involved in planning the water system. For such cases, simply prioritizing such research could help us glean what we can, after which subsequent development could proceed. Unprotected structures face a far greater threat. In conjunction with historical records, we have identified archaeological remains in a much larger $9.79 km^2$ area (Fig. 1b). Note that some of these remains lie just outside the Protected Area (Fig. 2b, which shows one unexplored temple mound to the south and three further mounds to the north), and some lie slightly outside the Buffer Zone (Fig. 1b). These unprotected structures face elevated risk of damage, particularly as nearby development activities are likely to intensify now that the site has acquired World Heritage status. As the next Case Study shows, this is not a hypothetical scenario.

CASE STUDY 2: **Bodhgaya**

Bodhgaya, which is the site of Buddha's enlightenment, was inscribed as World Heritage in 2002. Fig. 3 (left) shows a satellite image from late 2003 as well as the Core and Buffer-1 zones submitted to UNESCO. (The Buffer-1 zone extends 1 km in all directions from the Core zone). Within these zones, we identify several archaeological mounds, an ancient canal, and waterbodies through geospatial analysis.

It is clear from the more recent Fig. 3 (right) that by 2020, although the Core zone was well protected, several modern buildings had been constructed within the Buffer-1 zone (this is also reflected in the successive State of conservation reports of the WHC). Some of these constructions abut archaeological features and diminish their contours. At non-ASI sites such as Bodhgaya, other governmental agencies are authorized to forbid development within these zones if they are close to remains of cultural heritage. However, since these agencies have finite resources, they cannot always prevent unauthorized development. Since BHUVAN does not list any information about non-ASI sites such as Bodhgaya, it is difficult for other stakeholders (including concerned citizens) to alert authorities about potentially unauthorized development within this zone.

Fig. 1: (a) Protection boundaries around the heritage site of Nalanda, (b) Core and Buffer zone contextualized in the larger expanse of archaeological remains

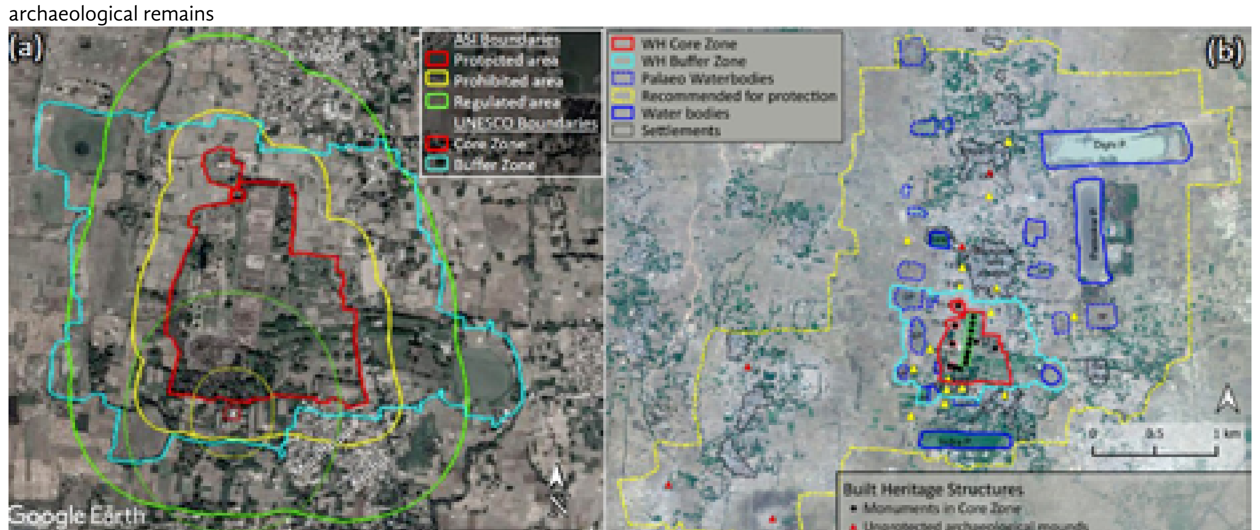


Fig. 2

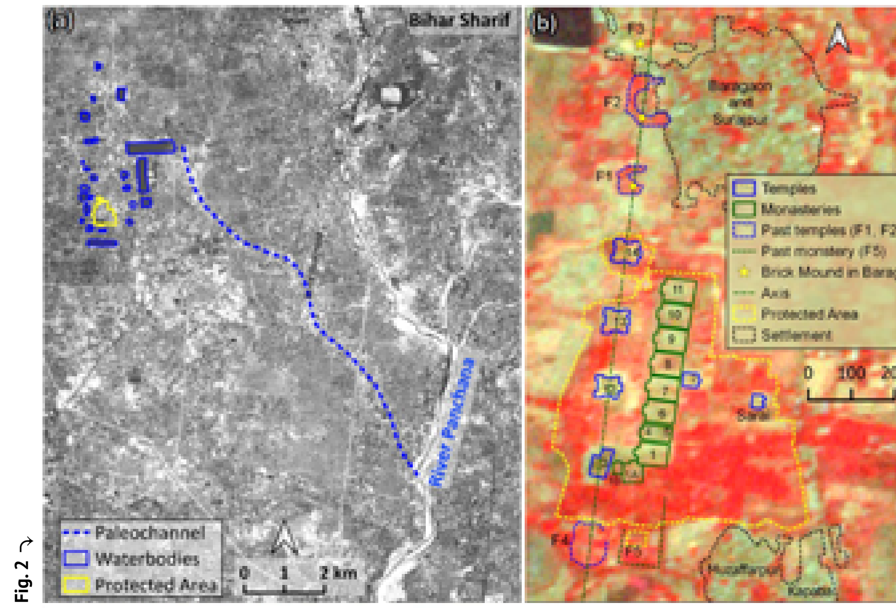


Fig. 3

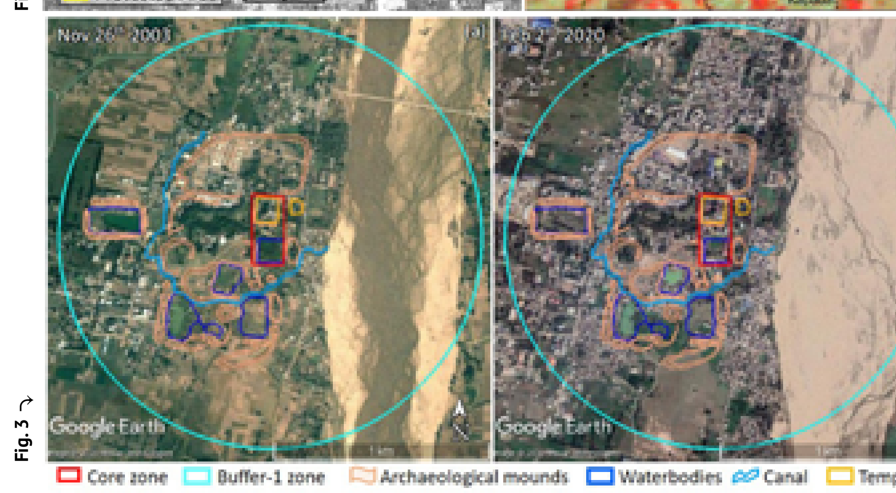


Fig. 4

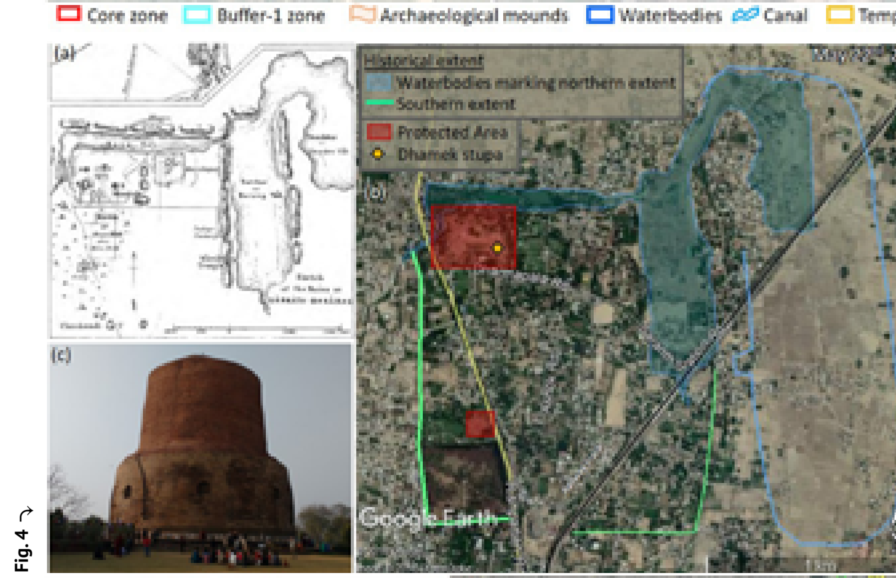


Fig. 5

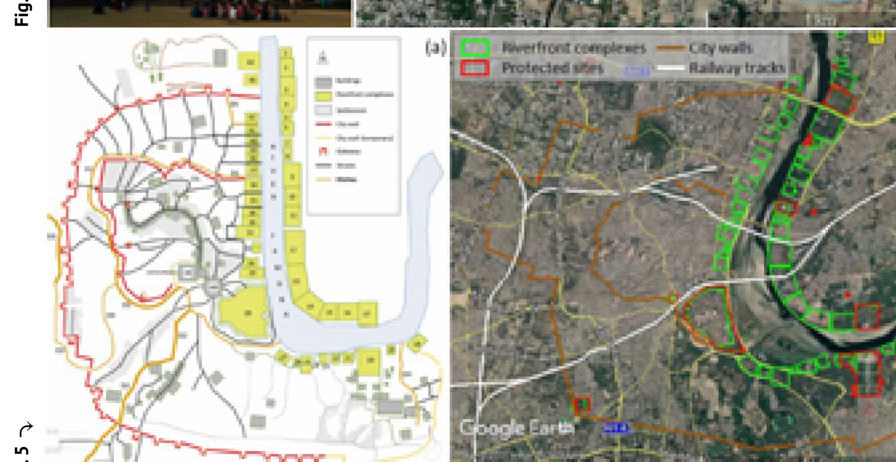


Fig. 2: (a) Nalanda's Protected Area amidst cluster of waterbodies and a paleochannel and (b) Unexcavated mound in the immediate vicinity of the site

Fig.3: The property of Bodhgaya inscribed as a World Heritage site in 2002 in the context of the archaeological landscape identifiable through geospatial analysis. Note the increased number of concrete structures from 2003 (left) to 2020 (right).

Fig. 4: Sarnath (a) Archaeological extent visible in 1861 (sketch by Alexander Cunningham);(b) archaeological landscape disintegrated by roads and railway track identifiable through geospatial analysis; (c) Dhamek stupa, the iconic monument of Sarnath

Fig. 5: Agra (a) A drawing adapted from map of Mughal Agra made by Sawai Jaisingh in 1720, showing a town with 50 riverfront complexes flanking either sides of river Yamuna with a settlement to its west enclosed by 2 tiers of city walls; (b) a Google Earth image showing the locations of key features marked in Jaisingh's map in the context of crisscrossing roads and railway lines.

Fig. 3 clearly indicates that protection boundaries are a double-edged sword. Once they are set, they protect the structures within while simultaneously heightening the threat to structures outside. This risk is heightened at World Heritage sites, as redevelopment projects aim to cater to the growing number of visitors. Hence, site protection boundaries must be selected with utmost care.

Proposed Policies:

1. The historical extent of a cultural heritage site based on geospatial analysis should be considered when determining its Protected Area

A careful study of the landscape in the vicinity of a site using satellite imagery can lead to two important types of discoveries that may improve our overall understanding of the site: the discovery of further instances or attributes of built heritage, and the discovery of artefacts such as former water bodies, canals, and mounds associated with past human activity at the site. This geospatial analysis must be integrated with historical spatial records such as old maps, records, paintings, and field surveys to estimate the site's historical extent. The distribution of confirmed and probable authentic remains within this extent should be considered, in addition to traditional on-site exploration and surveys, to determine the Protected Area for the site.

The onus for identifying the historical extent must rest with the academic research community for two main reasons. First, there is often insufficient evidence to precisely determine a site's historical extent. Hence, any proposed historical extent must be evaluated based on a peer review of objective facts. This includes evaluating fresh evidence, such as data obtained using new technologies. Second, there is no uniform or formulaic approach to geospatial analysis of all cultural heritage sites, because the process of analysis is sensitive to variations between sites. Hence, a peer review of the techniques applied is necessary before the analysis can be relied upon.

2. Adequate funds must be provided to conduct geospatial analysis at all sites

When compared to traditional on-site exploration and surveys, geospatial analysis is extremely efficient, both in terms of time and cost. Unfortunately, there is presently a lack of capacity to conduct such an analysis for all sites in a short period of time. Hence, the following steps should be taken:

a. Prioritise rapidly developing areas. As we have seen, many archaeological remains are inadequately protected. In areas where rapid development is underway or imminent, it is necessary to perform geospatial analysis on priority. This includes all sites inscribed as World Heritage sites where, as noted earlier, sustained developments due to high tourist footfall can be expected.

Fig. 6: Armoury of Tipu Sultan at Srirangapatna located near the railway station (photo taken post relocation). A series of Google Earth images showing it locations before and after relocation.

b. Training. Institutions with the necessary expertise should be provided support to run training programmes for ASI, State Departments of Archaeology, and other partner institutions so that geospatial analysis of sites can be rapidly scaled.

Multiple sources should be tapped for funding for these activities, including Government, Industry CSR funds, philanthropy, as well as regional and international organizations who may have interests in protecting specific sites, or sites in specific regions. Finally, continued research funding for applications of science and technology to study cultural heritage landscapes is crucial to sustain research in new techniques and in leveraging new technologies.

3. A national-level geospatial database of all cultural heritage landscapes must be created and mandatorily consulted prior to authorizing any development

The negative impact of developmental activities on India's cultural heritage is not a recent phenomenon. For instance, several 19th century public works projects caused significant damage to cultural landscapes at Sarnath and Agra (see Fig. 4 and 5). If there is lack of awareness about the extent or value of archaeological heritage present in a region, even authorized developmental activities can cause significant damage. Therefore, it is imperative to create and maintain a geospatial database that identifies archaeological landscapes. Further, this authoritative resource must be made available publicly and referenced while authorizing all development. This will at least ensure that any decision to favour development over heritage preservation is taken with relevant facts available to both decision makers and citizenry, as befits a healthy and vibrant democracy.

The absence of such a database can lead to significant economic losses, as illustrated in Srirangapatna. One of Tipu Sultan's armouries was located very close to the railway tracks. When the track-doubling project was proposed, a database that listed this historic structure would have alerted planners to the problem. At this early stage, the public could have been informed of the need to either demolish this historic structure, or to consider alternatives with a range of associated costs. Unfortunately, the project was sanctioned and later stalled by the awareness of the structure. The government then proposed relocating the armoury (Fig.6) at significant additional expense, when it was too late to consider less expensive or less disruptive alternatives.

Unlike a database such as BHUVAN, this resource must include not just confirmed and protected sites, but also potential remains of cultural heritage identified through geospatial analysis. This database should be regularly updated based on new research findings.

Finally, the database must be publicly accessible so that agencies involved in cultural heritage protection, as well as concerned citizens, can assist with monitoring changes to land use in the vicinity of sites, and to alert authorities in charge of their protection in case anything suspicious is observed. Efforts to sensitise communities to their local cultural heritage can begin even at the school level, in line with the recommendations of the National Education Policy 2020 (4.29, p.16).

Concluding remarks

We are fortunate that so much of our built heritage has survived, and some of these surviving remnants have not yet been discovered. While it may not be feasible to protect everything of historical significance, finding as much of what has survived is far less costly. Our interest therefore is to find and record as much of our cultural heritage as quickly as we can, so that we can make carefully considered decisions on what we must preserve. If we must forego something, it should only be due to a lack of resources, or competing demands in the public interest – but never because we were unaware that it had survived. ☐

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PROGRAMS

Summer School for Women in Mathematics and Statistics
14—21 June 2021 ✦ *Organisers* — Siva Athreya and Anita Naolekar

Online School and Discussion Meeting on Trapped Atoms, Molecules and Ions
10-22 May 2021 ✦ *Organisers* — Bimalendu Deb, Sourav Dutta and Saikat Ghosh

Non-Hermitian Physics
22-26 March 2021 ✦ *Organisers* — Manas Kulkarni and Bhabani Prasad Mandal

Probabilistic Methods in Negative Curvature
1-12 March 2021 ✦ *Organisers* — Riddhipratim Basu, Anish Ghosh and Mahan M.J.

OUTREACH

Kaapi With Kuriosity has been temporarily renamed Kuriosity During Quarantine. All talks are held online.

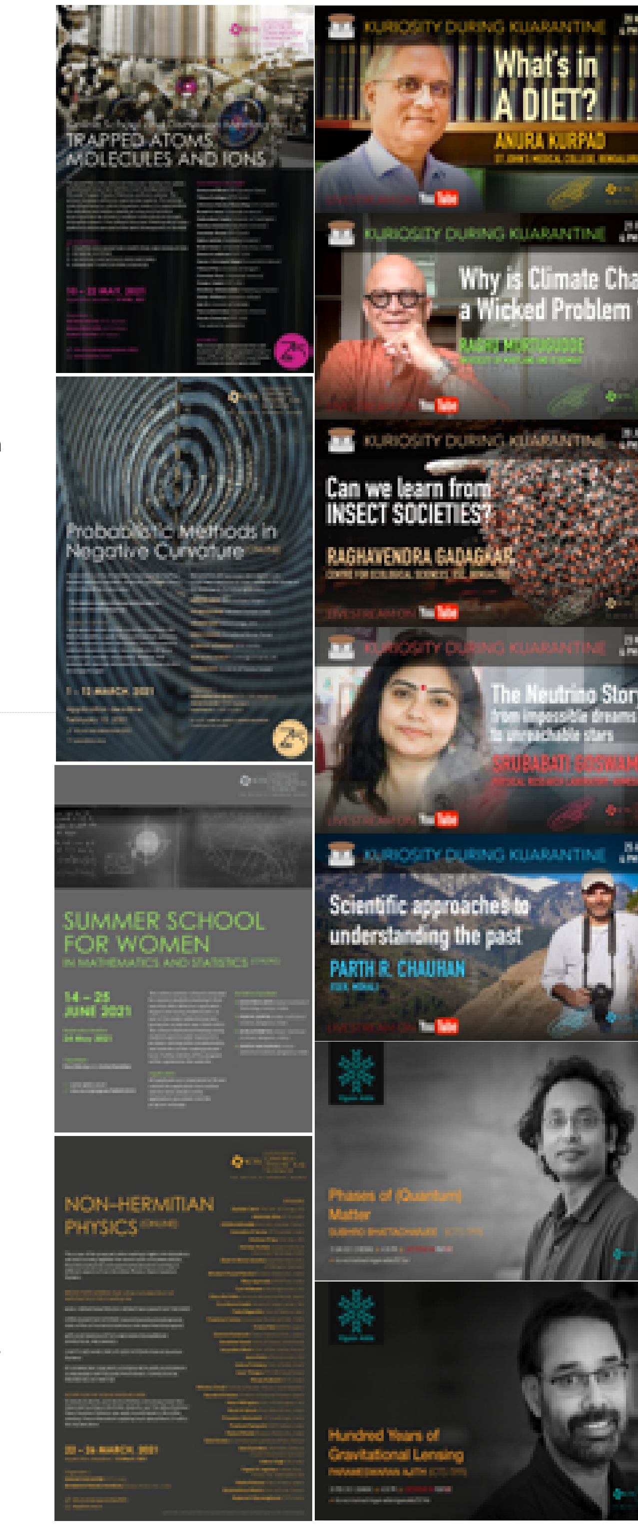
KURIOSITY DURING QUARANTINE

Can We Learn From Insect Societies?
20 June 2021 ✦ *Speaker:* Raghavendra Gadagkar
(Indian Institute of Science, Bangalore)

The Neutrino Story: From Impossible Dreams to Unreachable Stars
23 May 2021 ✦ *Speaker* — Srubabati Goswami
(Physical Research Laboratory, Ahmedabad)

Scientific approaches to understanding the past
25 April 2021 ✦ *Speaker* — Parth R. Chauhan *(Indian Institute of Science Education and Research, Mohali)*

What's in a Diet?
28 March 2021 ✦ *Speaker* — Anura Kurpad *(St John's Medical College, Bengaluru)*



Why is Climate Change a Wicked Problem?
21 February 2021 ✦ *Speaker:* Raghu Murtugudde
(University of Maryland and IIT Bombay)

VIGYAN ADDA

Phases of (Quantum) Matter
15 June 2021 ✦ *Speaker* — Subhro Bhattacharjee
(ICTS-TIFR, Bengaluru)

Hundred Years of Gravitational Lensing
28 February 2021 ✦ *Speaker* — Parameswaran Ajith
(ICTS-TIFR, Bengaluru)