# InScight

The IISER Kolkata Science Magazine

#4 | July 2025

**THROUGH THE EYES OF THE FOUNDING DIRECTOR**
Interview with Prof. Dattagupta

**A CENTURY OF QUANTUM MECHANICS**
From Paradoxes to Possibilities

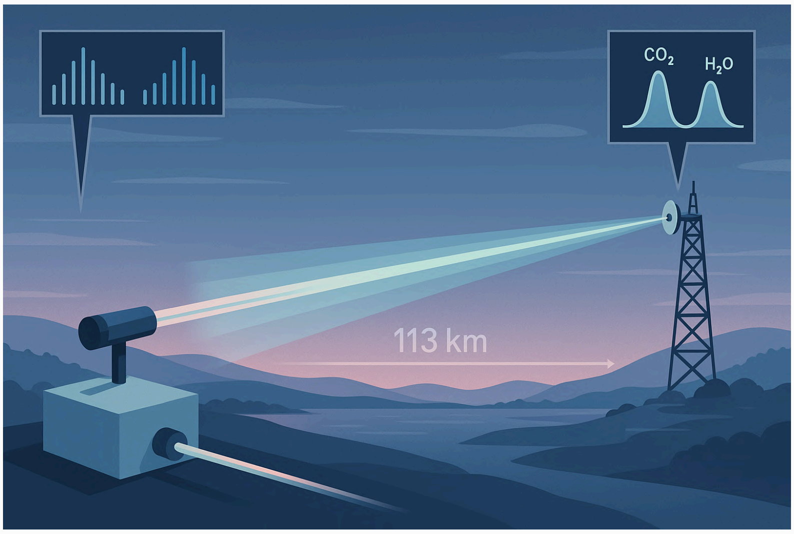
**THE QUEST FOR THE SEA'S BLUE**
Comic on the Raman Effect

# The Celebration of Science For A Better Future

## *Foreword by Prof. Tapas Kumar Sengupta*

Science is the celebration of unravelling the mysteries of our evolving universe. Unravelling the existence and functions of galaxies involved in formation of stars, planets and evolution of life itself on our beloved blue planet. Through observations, studies and discoveries of the true facts we practise science in our everyday life. Our scientific studies made us able to understand the importance of the ecosystem and its conservation, necessity of food production and storage, combating and preventing diseases and innovation of new, better and safer therapy, safer energy production and its sustainability, faster communication and making artificial intelligence as a new tool.

As we cannot freeze any condition forever, contentious studies and scientific experimentations are required to understand the ever-changing ecosystem and need of our civilization and to come up with more and more innovations in order to address those changes to make our planet more habitable.




**In this experiment, two laser frequency combs—one on each end of a 113 km open-air path—beam precisely timed light pulses across the atmosphere to detect gases like $CO_2$ and $H_2O$ with extraordinary precision. Read the relevant writeup by Debanuj Chatterjee.**

**Prof. Mitra explains the phenomenon of zero shadow day to the introductory summer school students at the Inter-University Centre for Astronomy & Astrophysics (IUCAA). Read his interview.**

For that, besides the traditional scientific studies and standard scientific research, out of the box thinking is required for seeding and cultivating young minds for innovations. Let *InScight* be the platform for the Insight of our future to seed, cultivate and nurture the open minds and unbound thoughts of the young scientists.

After the first release of *InScight* in the month of January in 2025, this journey is going on with a clear motivation and with fullest energy and enthusiasm to publish the fourth issue. My sincere thanks to the InScight team for having such an endeavour. Keep going, keep doing and thinking about science. Very best wishes to the team InScight.

# A Word From The Editor

Hello Friends! Welcome to the fourth issue of InSight. As we celebrate the turning of another issue, I take this opportunity to thank you all who have stood with us, and helped us to continue this journey of InScight Magazine - The IISER Kolkata Science Magazine. Filled with vibrant stories and voices of our alumni, Professors, and guest scientists, this month, we have tried to add colour to the magazine and take the readers on a journey through the history of IISER Kolkata and also to newer domains of Science today.

As Prof. Ayan Banerjee has rightly mentioned, in his words, Science is a method and an attitude, and Prof. Tapas Kumar Sengupta, in his foreword to this issue of InScight Science, is the celebration of unravelling the mysteries of our evolving universe - it is our duty as scientists, who are funded by the tax paid by the commoners, to come out of the labs and take our research to the mass. InScight envisions bridging the gap between distance between the scientists and the masses in the upcoming days.

In this issue, we have featured our alumni from the Department of Physical Sciences - Dr. Rajarshi Bhattacharyya, who is currently working in Germany as a Cryogenic Systems Engineer at attocubes systems AG. We believe that his journey from a BSMS student at IISER to PhD scholar in Israel and finally now as a professional engineer in Germany would show you all a newer perspective of the higher education and job market after BSMS.

In the other two interviews, we have featured Prof. Sushanta Dattagupta - the founder director of IISER Kolkata, and Dr. Sanjit Mitra of IUCAA - a leading scientist of the LIGO-India project, and we hope the interview with them shall help you all in your journey forward.

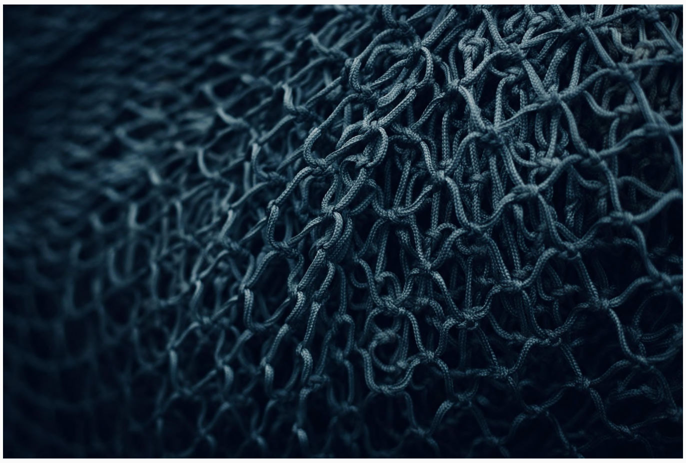
We have started a new section in the magazine, where we advertise academic internships, PhD positions, and Post-Doctoral applications, gathered by scraping the internet and email conversations. We believe that this section will help the students plan accordingly and in advance for their upcoming academic and scientific journey. Of course, we by ourselves cannot gather all the news that can be gathered, so we request all our readers to bring such information to our notice, so that we can better distributed the information.

We are planning on adding a new section to the magazine - write about your PhD thesis! The point is to discuss the story of your PhD thesis; the questions, the results and the philosophy of your approach, written so that students across the disciplines can understand and have a feel for it. We aim to tighten the research community of IISER Kolkata across disciplines, and who knows - you may find a newer possibility and a collaboration for your project too!

We are always looking for your contributions and feedback. Thank you for journeying with us. On behalf of the entire team, happy reading—and here's to building bridges, one insight at a time.

With warmth,

**Swarnendu Saha,**
**Editor-in-chief,**
**InScight**



Knots are hard to untie, making them robust. Sukalyan Deb's article explores how similar robustness emerges in properties of certain quantum systems.

Dicover how a simple question - why does the sea look blue - led to one of the most groundbreaking discoveries in physics. This engaging science comic traces C.V.Raman's journey to uncover the phenomenon that now bears his name.

# In This Issue

# Academic Listings: Internships, PhDs, Post-docs

## INTERNSHIPS

**DoS/ISRO Internship & Student Project Trainee Schemes**
⏰ **Deadline**: varied
📎 **Website**

**Research Internship at OIST**
⏰ **Deadline**: 15/10/25
📎 **Website**

**Visiting Student Research Program at KAUST**
⏰ **Deadline**: rolling
📎 **Website**

## PHD POSITIONS

**Max Planck Institute for Informatics - PhD Applications**
⏰ **Deadline**: rolling
📎 **Website**

**IMPRS – Solar System Science (Astrophysics) – Göttingen & Braunschweig**
⏰ **Deadline**: 1/10/25
📎 **Website**

**The International Max Planck Research School on Astrophysics at the Ludwig Maximilians University Munich**
⏰ **Deadline**: 1/11/25
📎 **Website**

**UC Berkeley's Physics Graduate Program**
⏰ **Deadline**: 15/12/25
📎 **Website**

**Arizona State University Physics PhD Admission**
⏰ **Deadline**: 31/1/25
📎 **Website**

**Univerity of Denver Physics - PHD**
⏰ **Deadline**: 8/9/25
📎 **Website**

**Curtin University, John de Laeter Centre PhD Scholarships**
⏰ **Deadline**: 1/8/25
📎 **Website**

**Graduate Research Assistantships (Ph.D.) in drought and dust flux, Northern Great Plains, U.S**
⏰ **Deadline**: 14/8/2025
📎 **Website**

**Exoplanet Characterisation Predictions via Gravitational Microlensing: Competition Funded PhD Project**
⏰ **Deadline**: rolling
📎 **Website**

## POSTDOCTORAL AND OTHER SHORT-TERM POSITIONS

**Stanford Postdoctoral Recruitment Initiative in Sciences and Medicine**
⏰ **Deadline**: 26/8/25
📎 **Website**

**U.S. Naval Research Laboratory Post-Doctoral Fellow (Coastal / Sea Ice Remote Sensing)**
⏰ **Deadline**: 8/8/25
📎 **Website**

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| **North Arizona University Postdoctoral scientist position: Greenhouse gas emissions modeling and mapping** | ⏰ **Deadline**: 6/8/25<br>📎 **Website** |
| **Marine Biomedical Postdoctoral Fellowship at Mote Marine Lab and Aquarium** | ⏰ **Deadline**: 14/8/2025<br>📎 **Website** |
| **John S. Foster, Jr. Postdoctoral Fellowship and the Harold Brown Postdoctoral Fellowship** | ⏰ **Deadline**: 11/8/2025<br>📎 **Website** |
| **Advanced Study Program (ASP) Postdoctoral Fellow I** | ⏰ **Deadline**: 8/8/2025<br>📎 **Website** |
| **Postdoctoral Scholar in Oxygen Dynamics - Scripps Institution of Oceanography** | ⏰ **Deadline**: 15/8/2025<br>📎 **Website** |
| **Project Associate, Studying protein folding and aggregation using computer simulations, IMSc (India)** | ⏰ **Deadline**: 31/07/2025<br>📎 **Website** |

# A Century of Quantum Mechanics: From Paradoxes to Possibilities


## Sobitri Sen (Ashoka University and IISER Kolkata)



Quantum mechanics, turning 100 in 2026, has reshaped our understanding of nature - from atoms and subatomic particles to emerging technologies like quantum computers and ultra-precise sensors. This article traces its historical origins, outlines its expanding role across physics, chemistry, biology, and engineering, and highlights the deep questions that still remain.


*Also available online, at scicomm.iiserkol.ac.in*


**REVIEWED BY**
Abhirup M, Ayan B and Sharanya C

**SUBMITTED**
Mar 10, 2025

**CATEGORY**
Physics

**Dr. Sobitri Sen** is a teaching fellow at Ashoka University (Sonepat, India) and a visiting scientist at the QuantAct Laboratory at IISER Kolkata. She is a curious mind who feels and writes about scientific topics using literature to make it a treat to read!

In 2026, the global scientific community will celebrate 100 years of quantum mechanics - a theory that has transformed how we understand nature and helped shape today's technologies. Born in the early 20th century from experiments that defied the rules of classical physics, quantum mechanics has since become central to physics, chemistry, materials science, computing, and even our understanding of life itself. As we mark this centennial, this article looks back at its historical origins, explores how it continues to shape new discoveries, and considers what the next century of quantum science may bring.

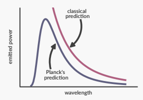

FIG 1: Comparison of classical and quantum predictions for blackbody radiation. The classical Rayleigh–Jeans law (pink curve) incorrectly predicts an infinite amount of emitted energy at short wavelengths, leading to the ultraviolet catastrophe. Max Planck resolved this paradox by assuming energy is emitted in discrete quanta, giving rise to the correct spectrum (violet curve).

## A Historic Journey: Why Quantum Mechanics Was Needed

Prior to the advent of quantum mechanics, physics was considered mostly complete through **Newtonian mechanics** and **Maxwell's electrodynamics**. However, through the nineteenth and early twentieth centuries, significant experimental results were discovered that challenged classical predictions.

The first major challenge came from **blackbody radiation**. According to the Rayleigh-Jeans law, classical physics predicted that hot objects emit arbitrarily large amounts of energy at higher frequencies, leading to the infamous **ultraviolet catastrophe**. In 1900, **Max Planck** resolved this paradox by proposing that energy is absorbed only in discrete packets, or **quanta** [1] (the word **quantum** originates from the Latin word "**quantus**," meaning "how much,"!).

A few years later, **Albert Einstein** extended this idea to light itself. His 1905 explanation of the **photoelectric effect** showed that light behaves as if it's made up of individual particles - later called **photons** - rather than just waves [2]. This challenged the long-standing belief that light was purely a wave, and hinted that nature might be more discrete than continuous.

Further inconsistencies emerged in the field of **atomic physics**. According to the laws of classical electrodynamics, an electron orbiting the nucleus should continuously lose energy by emitting electromagnetic radiation and spiral inward into the nucleus, leading to the **collapse of atoms**. This was of course at odds with the observed atomic stability in nature. To resolve this paradox, in 1913, **Niels Bohr** proposed his ground-breaking model of the hydrogen atom [3], where electrons occupy fixed **discrete energy levels**, and can transition between the levels only by absorbing or emitting definite amounts of energy**.** The fact that the electron cannot absorb or emit arbitrary amounts of energy prevented its collapse. While Bohr's model successfully explained the Balmer series (spectral lines to n=2) of hydrogen,the absence of a substantial theoretical foundation meant that it failed to describe more complex atoms.

The final blow to the fundamentals of classical mechanics came with the emergence of **Wave-Particle Duality**. **Louis de Broglie** (1924) introduced the idea of **matter waves,** proposing that, like light, electrons exhibit wave-like properties [4]. **Davisson and Germer** (1927) experimentally corroborated this concept by observing **electron diffraction** [5], demonstrating that electrons behave like waves under certain conditions.

These findings demanded an entirely **new theoretical framework**. In the mid-1920s, **Werner Heisenberg** and **Erwin Schrödinger** independently developed quantum mechanics, through matrix mechanics [6] and wave mechanics [7] respectively. Though they looked different, the two approaches turned out to be mathematically equivalent. Shortly afterward, **Paul Dirac** combined quantum mechanics and special relativity to predict the existence of antimatter [9]. All of these advancements combined to create modern quantum mechanics, introducing a new era of physics.

## Expanding Domains: Quantum Field Theory & Beyond

While early quantum mechanics worked well for predicting the behaviour of atoms and molecules, it had limitations.:

**it wasn't compatible with Einstein's special relativity, and** it couldn't account for situations involving the creation and destruction of particles (phenomena common in high-energy physics).

To address these limitations, physicists developed **Quantum Field Theory (QFT)** in the mid-20th century by merging quantum mechanics with special relativity.

At the heart of QFT is a simple but revolutionary idea: the fundamental building blocks of nature are not particles, but **fields** - mathematical objects that can take on values at every point in space and time [15]. Imagine space filled with invisible, vibrating fields, like a sea of tensioned fabric stretched across the universe. A particle, in this view, is just a tiny ripple or excitation in one of these fields. Each type of particle that we can observe or know to exist - electrons, photons, quarks - is tied to a different field. These fields can interact, combine, and exchange energy, allowing QFT to describe complex processes like particle collisions and the forces between them. [15].

This framework is the foundation of the **standard model of particle physics**, our best theory of fundamental particles and their interactions (excluding gravity) [16]. Within the standard model,

- quantum **electrodynamics** (QED) describes how light and matter interact [11, 12]. It is the most precisely tested theory in all of physics,
- quantum **chromodynamics** (QCD) explains the strong force that binds quarks together inside protons and neutrons, and
- **electroweak** theory unifies the above two forces into a single description [17, 18].

In one of the most climactic conclusions, the discovery of the **Higgs boson** at CERN in 2012 [19] confirmed the presence of the Higgs field that had been predicted for a long time and this completed the Standard Model. By interacting with the Higgs field, elementary particles such as quarks and electrons obtain mass, through the **Brout-Englert-Higgs mechanism** (or the Higgs mechanism in short).

## Expanding Technologies via Quantum Computing

In recent years, **quantum computing** has emerged as one of the most exciting frontiers in technology. Unlike binary classical switches, quantum states (quantum bits or **qubits**) can be both 0 and 1 at the same time, thanks to a phenomenon called superposition. Even more remarkably, these qubits can become **entangled**, meaning the state of one qubit is linked to another, no matter how far apart they are. These uniquely quantum properties allow certain tasks to be performed much faster than with classical computers [23].

You can think of a quantum computer like a massively **parallel multitasker**, exploring many computational paths at once, whereas a classical computer checks them one at a time. By leveraging these properties, quantum algorithms often offer massive speedups compared to their classical counterparts. **Shor's quantum algorithm** can factor large numbers much faster than classical methods,

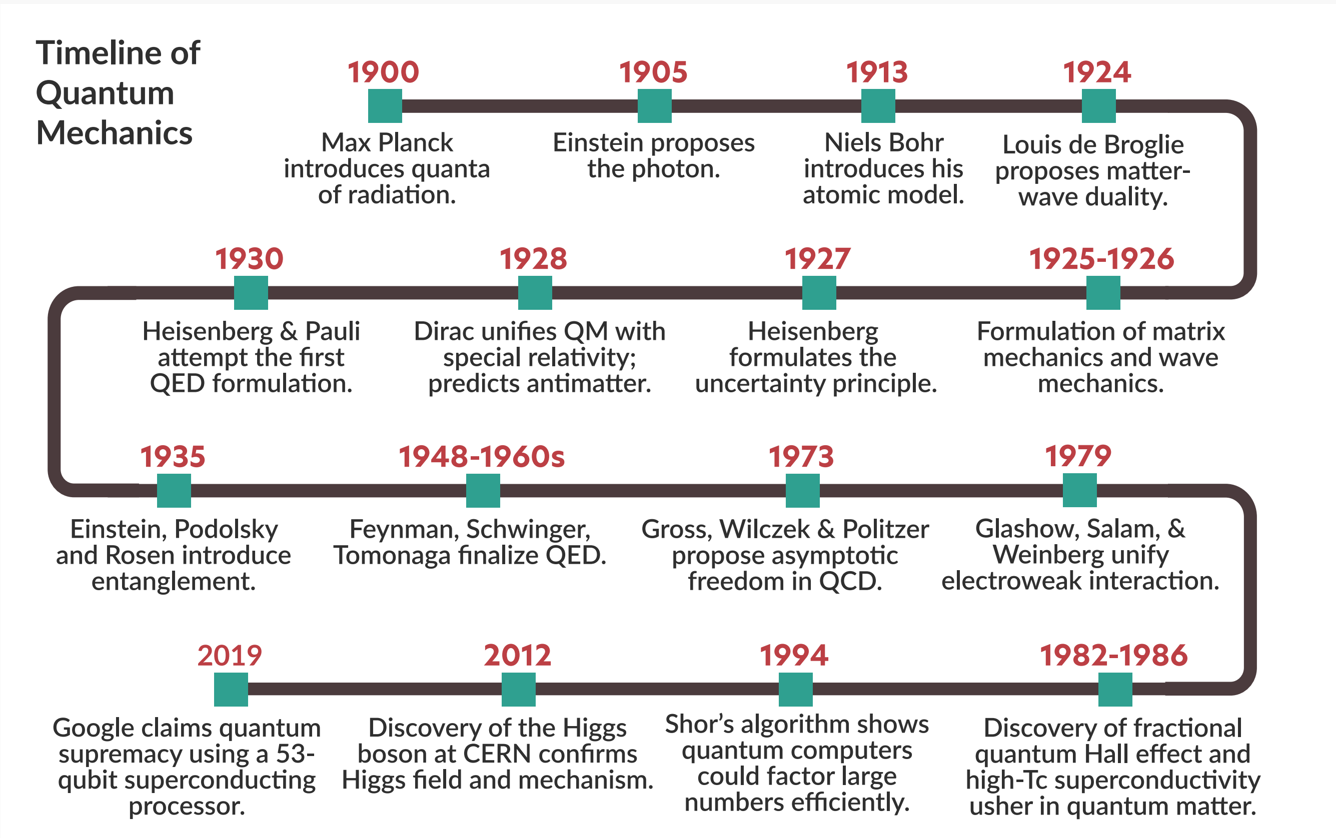


FIG 2: A visual journey through the major milestones in the development of quantum mechanics over the last century. Key moments include Planck's proposal of quanta (1900), the advent of quantum field theory (1928), the development of quantum algorithms (1994), and the discovery of the Higgs boson that completed the Standard Model (2012).

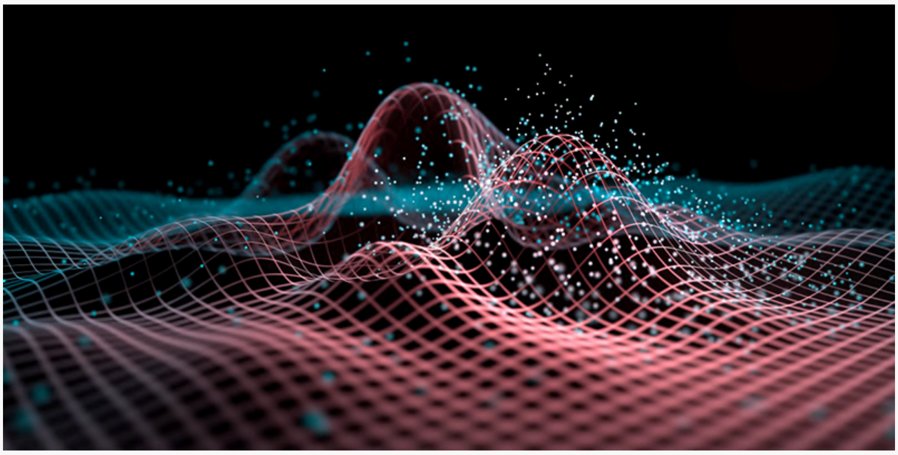

**FIG** 3: The central idea of quantum field theory (QFT) is that particles are not standalone entities, but localized excitations of underlying quantum fields permeating space. Each fundamental particle such as an electron, photon, or quark is associated with a specific quantum field that vibrates at every point in space and time. Interactions between particles arise from the interplay between these fields, such as when the electromagnetic field mediates forces between charged particles.

threatening current cryptography [24]. In addition, **Grover's algorithm** offers a quadratic speedup in search tasks [25].

However, unlike classical bits, quantum bits (or qubits) are extremely fragile and **prone to errors** due to decoherence and noise from their environment. This poses a serious problem for designing practical quantum computers that can operate reliably over long periods. Recent breakthroughs in **quantum error correction** and the development of **fault-tolerant architectures** have brought us significantly closer to building practical quantum computers [26]. Quantum error correction aims to safeguard information by encoding a single logical qubit into many physical ones, allowing the system to detect and correct errors without directly measuring the qubits themselves. Major tech companies such as **Google**, **IBM**, and **Microsoft** are actively pursuing scalable quantum processors [27, 42].

Meanwhile, **quantum communication** technologies are also making rapid progress. A prominent application is **Quantum Key Distribution** (QKD), which allows two parties to exchange cryptographic keys with security guaranteed by quantum mechanics [28]. Unlike classical encryption, QKD is fundamentally immune to eavesdropping, as any attempt to intercept the key disturbs the quantum system and reveals the intrusion. This technology could form the basis of ultra-secure communication networks in the near future.

## Real-World Applications: Chemistry, Biology, Materials Science, and more

Quantum mechanics has numerous real-world applications in science and engineering. In **quantum chemistry**, it helps scientists simulate how atoms bond to form molecules, enabling the design of new materials and accelerating drug discovery. Using quantum models, researchers can predict how molecules will interact in complex environments, such as inside cells or on catalytic surfaces [29]. In **quantum biology**, some natural processes appear to rely on quantum effects. For instance, plants may use quantum coherence to transfer energy efficiently during photosynthesis, and migratory birds might sense the Earth's magnetic field using entangled electron spins [30].

Quantum mechanics has also transformed our understanding of materials, leading to the discovery and engineering of exotic **quantum materials**. Notable examples include **topological insulators**, which conduct electricity on their surfaces but remain insulating inside, and **high-temperature superconductors**, which carry electric current without resistance at relatively high temperatures. These materials challenge traditional theories of matter and offer promising pathways for developing next-generation electronics, energy-efficient power systems, and quantum devices [31, 32].

Apart from materials, quantum mechanics also plays a key role in precision measurement techniques. **Atomic clocks**, the most accurate time-keeping devices on the planet, use the frequency of transitions between energy levels of cesium or rubidium atoms, and are used in global positioning systems (**GPS**) and gravitational wave detectors like LIGO. These applications illustrate the pervasive impact of the field across multiple disciplines [33, 34].

## Unfinished Business: Some Open Problems

Quantum mechanics is among the most successful and precisely tested theories in all of science, yet it still leaves many deep questions unanswered. We point out some of them here.

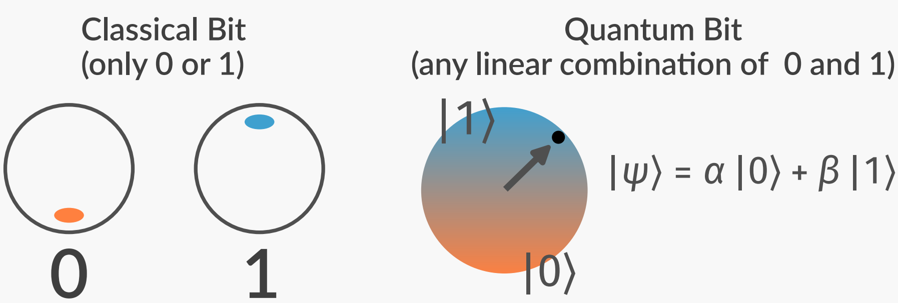


**FIG** 4: A comparison between a classical bit and a quantum bit (qubit). Classical bits can only be in states 0 or 1. Qubits, thanks to quantum superposition, can exist in any combination of both 0 and 1 simultaneously, enabling vastly more powerful computation in specific tasks. The ability to form superposition states is often expressed by saying that the qubit can occupy any point on the surface of a sphere (the bloch sphere).

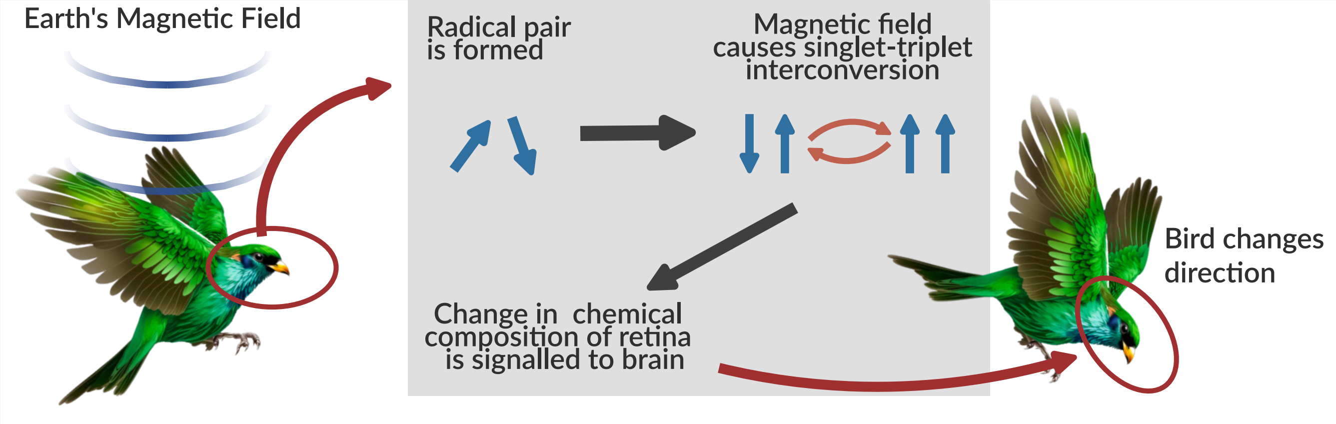


FIG 5: A conceptual diagram of how quantum entanglement may enable migratory birds to sense the Earth's magnetic field. A radical pair of electrons is formed in the bird's eye; these electrons respond to magnetic fields and undergo transitions in the retina, leading to modified concentration of chemical output compounds and provides sensory signals. Adapted from [43].

### The Measurement problem

Quantum theory predicts that a system evolves smoothly and predictably, according to the **Schrödinger equation** - the quantum analogue of Newton's second law of motion. This leads to a strange outcome: as mentioned earlier, particles can exist in **superpositions**, or combinations of multiple possible states at once. But whenever we measure such a system, we only see a **single outcome**. Why?

This puzzle is known as the **measurement problem**. It arises because the standard rules of quantum mechanics don't explain what exactly happens during a measurement or why the wavefunction **collapses** to one result. Is collapse a physical process? Is it just a change in our knowledge? Or is something deeper going on? No consensus exists yet.

Solving the measurement problem is crucial because it touches the very heart of quantum mechanics and of reality itself. It may be the key to explaining how the quantum world, with all its uncertainty and fuzziness, gives rise to the clear, definite experiences of the classical world we live in.

### An Overarching Theory For Quantum Matter

Since the landmark discoveries of **high-temperature superconductivity** and **fractional quantum hall effect** in the 1980s, scientists have come to realise that several materials with strong **inter-electron correlations** show exotic properties. The physics of such materials was found to be governed by (i) **topological** considerations (where global properties of the wavefunction determine the physics instead of local details) and (ii) strong **many-particle entanglement** (a phenomenon in which the configurations of multiple particles get locked with each other), and they have come to be known as quantum matter. Researchers are working to find unified frameworks that can explain how these systems behave and predict new materials with similar strange properties. A complete theory of quantum matter could revolutionize technologies like superconductors, quantum computers, and even generate new states of matter.

### Quantum gravity and unification

One of the biggest unsolved problems in physics is how to combine quantum mechanics with **general relativity** (Einstein's theory of gravity). While quantum mechanics works extremely well for tiny particles, general relativity describes how space and time behave on large scales, like planets, stars, and galaxies. But when both theories are needed, such as near a **black hole** or during the **Big Bang**, they lead to conflicting results. The challenge is that gravity, as described by general relativity, treats space and time as a **smooth, continuous fabric**. But quantum mechanics suggests that, at the smallest scales, this fabric should be made of discrete chunks - like pixels in an image. When scientists try to apply the methods of quantum field theory to gravity, the math blows up with infinities that can't be handled, a problem known as **non-renormalizability**.

Various approaches (string theory, loop quantum gravity, etc.) attempt a unification, but no fully successful theory has emerged. Until **quantum gravity** is solved, our understanding of the universe's origin, black holes, and the deepest laws of nature remains incomplete. This problem is significant because it stands at the foundation of all physics: without it, we cannot claim to have a **complete theory** that covers both

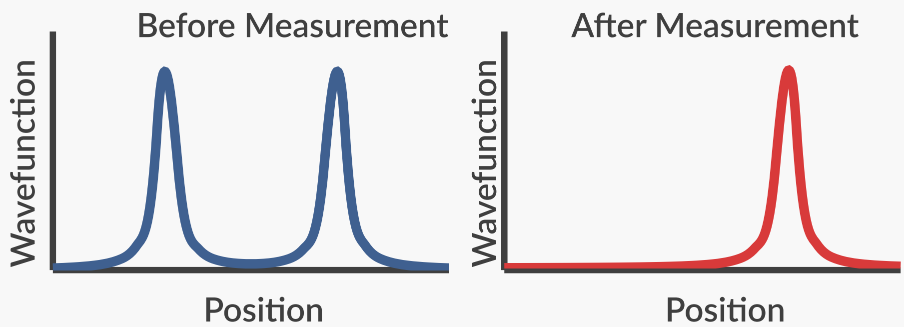


FIG 6: A schematic showing how a quantum system's wavefunction (which describes the probability of a particle's position) evolves from a spread-out superposition to a sharply defined outcome after measurement. This sudden transition, not fully understood, is at the heart of the measurement problem in quantum theory.


FIG 7: Requirements and Realizations of Qubits in the Second Quantum Revolution. This diagram summarizes the central criteria a physical system must meet to function as a viable qubit (inner circle), alongside a range of physical platforms where qubits have been implemented (outer circle). Core requirements include the ability to initialize qubits in a known state, apply fast and precise quantum gates, maintain coherence long enough for computation, and read out results with high fidelity. Adapted from [44].

the very large (cosmology) and the very small (quantum particles).

## Looking Ahead: The Next Century of Quantum Mechanics

As quantum mechanics turns 100, it remains one of the most vibrant and forward-looking areas of science. One emerging frontier is **quantum thermodynamics**, where researchers are exploring technologies like **quantum heat engines** and **quantum batteries** - devices that could one day store and convert energy far more efficiently than anything classical physics allows.

The coming years may also bring what physicists call a **second quantum revolution** - a new era driven by quantum technologies that promise to transform computing, communication, and sensing. From unbreakable encryption to faster-than-ever computation, quantum mechanics is poised to impact industries and everyday life in ways we are only beginning to imagine. In 2026, the global scientific community will mark this centennial milestone with lectures, exhibitions, and conferences hosted by institutions such as CERN, the Max Planck Institute, and the American Physical Society.

It's a moment not only to celebrate how far we've come, but also to look ahead. Because if the past century of quantum mechanics has taught us anything, it's that the quantum world is full of surprises. And we've only just begun to explore it.

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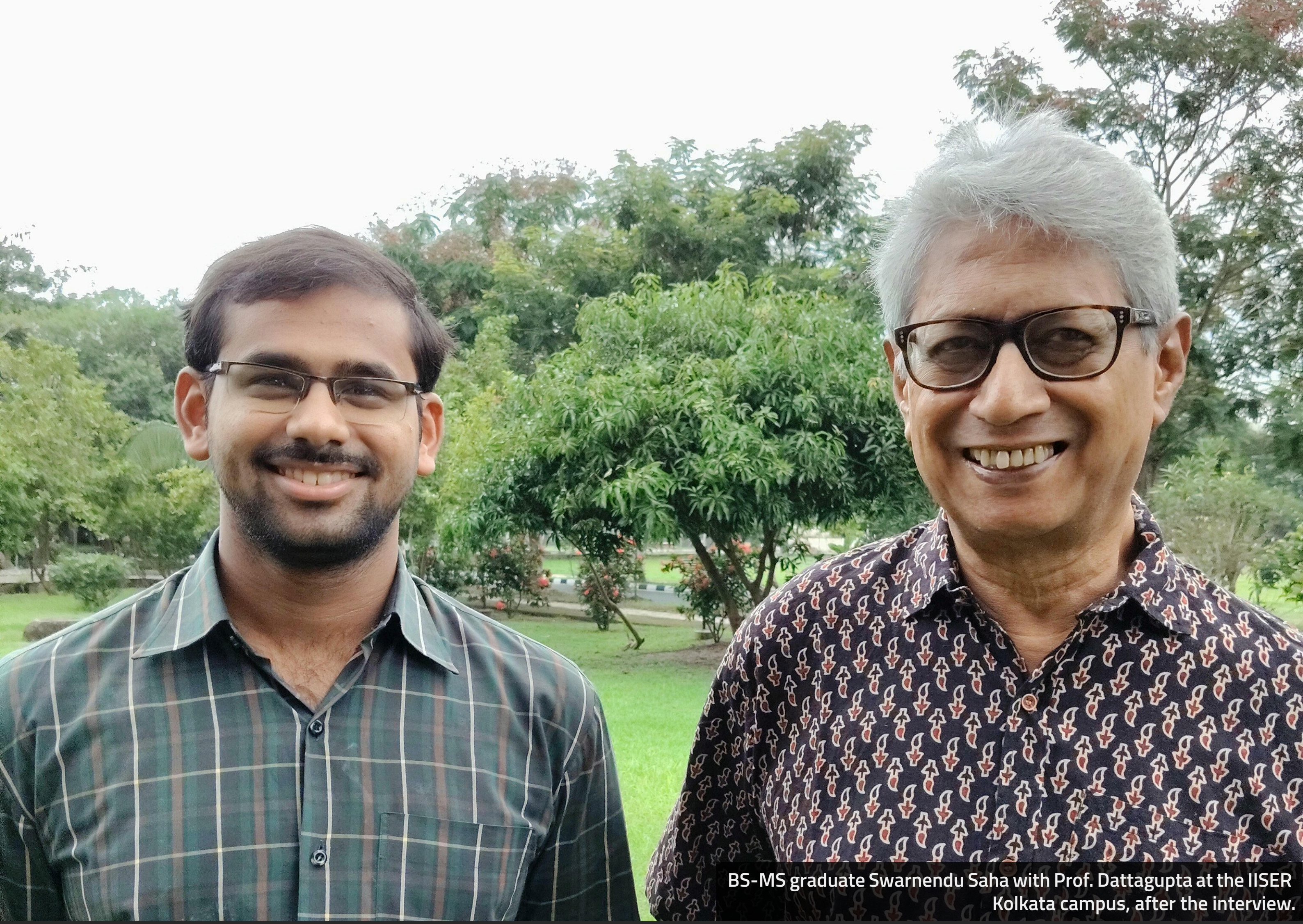

BS-MS graduate Swarnendu Saha with Prof. Dattagupta at the IISER Kolkata campus, after the interview.

# Through The Eyes Of The Founding Director: Interview with Prof. Dattagupta


## Swarnendu Saha (IISER Kolkata)


"You have to do what makes you happy, what brings you peace, and what makes you feel that you are your own person. You hold your own destiny in your hands." says renowned condensed matter physicist Prof. Sushanta Dattagupta. As the founding Director of IISER Kolkata, he reflects on the interdisciplinary spirit of IISERs, critiques academic gatekeeping, and urges students to seek fulfillment over mere careers.

*Also available online, at scicomm.iiserkol.ac.in*

**SS:** Hello, sir. I am Swarnendu Saha from Team InScight and a BSMS student here. I welcome you to this interview session with InScight.

**SDG:** Thank you, Swarnendu.

**SS: You were the founding director of IISER Kolkata and remain closely associated with it. Now, almost 16 years later, how do you see IISER Kolkata today? Has it stayed true to the original vision, or has the direction changed?**

**SDG:** Thank you for having me. First, it's actually been 19 years - we started in July 2006. At that time, IISER Pune and IISER Kolkata were the first two IISERs. Pune had the advantage of being adjacent to NCL, which provided access to facilities like water, power, and even lab space, including for NMR. We, however, started with nothing. The government channeled our initial funding through IIT Kharagpur, which gave us space in its Salt Lake campus. That's where we began in July 2006. I was the only faculty member, and there was just one attendant - Ajay, who is still here.

To start teaching, we borrowed faculty from institutions like Calcutta University, Jadavpur University, IIT Kharagpur, Bose Institute, SN Bose Centre, and others. Recruitment had to begin from scratch. Once faculty were hired, we needed lab space, which we got at NITTTR Kolkata. So, between Salt Lake (IIT Kharagpur), and NITTTR, we began to grow. We also received faculty housing from NITTTR. By then, we had about 20–30 faculty members.

**SS: Prof. Tapas Kumar Sengupta was among them, right?**

**SDG:** Yes, in biology. In chemistry, we had Balaram Mukhopadhyay, Swadhin Mandal, Sanjio S. Zade. They were among the first recruits. In physics, we had mostly theorists at first; experimentalists joined later. In earth sciences, there were Somnath Dasgupta and Nibir Mondal, who had a lab at IIT Kharagpur. NITTTR provided some labs, but we needed our own campus. At that point, we approached the Ministry and the then Chief Minister, Shri Buddhadeb Bhattacharya. He said land in areas like Rajarhat or Newtown would cost around ₹20 crores per acre, with only 20 acres available - adding up to ₹400 crores, nearly all of our initial ₹500 crore seed funding (which increased soon after). It was financially not viable.

But I also believed in the historical precedent of institutions starting modestly - like IIT Kharagpur, which began in Hijli Jail, or IIT Kanpur, which dealt with dacoity issues early on. Great institutes don't need to be in cities; they can grow in rural settings too. Fortunately, through the Chief Minister's intervention, we received nearly 210 acres of land at Mohanpur for just one rupee - essentially free. But then, we were still grappling, because while the space was given, construction had to be done. And you might know that this area is very fertile, also it's very soft land, because the river was very close.

Then the river moved away a little bit towards Hongsheshwari Mandir and all that. So, because of the softness of the land, you know, we had to do the foundation and all that. We had a wall, but then we needed some building space. We wanted to move, because by that time, faculty recruitment had started. We ordered two NMR facilities, 400 megahertz and 500 megahertz, x-ray, basic rudimentary things for physics and chemistry experiments, and a small animal house for biology. So, we decided to shift. We shifted here, I think, on the National Science Day, which is 28 February of 2009. We had then Governor Gopalakrishna Gandhi come and inaugurate the Raman Building. We basically got, through the West Bengal government, some old dilapidated buildings, which are adjacent to this campus that we are in now, which are in what is called the old Haringhata area, adjacent to Vidhan Chandra Krishi Vidyalaya and the University of Animal and Fishery Sciences.

And so, we reconstructed those buildings, like one building became the AJC Bose building. Those buildings were already there but in rather dilapidated condition. They were basically just left there, lying there as parts of either Bidhan Chandra Krishi Vidyalaya or Animal and Fishery Sciences under the West Bengal government. And there were also many hostel buildings, we renovated all of them. The new hostel building was called APC Ray Hostel Building. Another new building was called JC Bose Building, which is very scenic, next to the canal. And we even had a hut there, where we could congregate after every seminar for tea.

So, it gave an impression of almost like Cambridge actually. This is a very, very green campus. So, what I was going to say earlier was this, because of the fertility of the land, this area is very green and you throw anything, it grows, you know. So, I'm just making a preamble to coming to the campus now. The JC Bose Building, the Raman Building, you know, had absorbed many experimental facilities. Like in the ground floor, we had the two NMR machines looked after by Swadhin Mandal. He


**FIG** 1: Sushanta Dattagupta obtained his BSc. and MSc. degrees from the University of Calcutta in 1965 and 1967 respectively.

had some glove boxes and also inorganic chemistry facilities. Balaram Mukhopadhyay had his lab on organic chemistry. Chiranjib Mitra had his PPMS (physical property measurement system) and MPMS (magnetic property measurement system) and also the other measurement system.

Bipul Pal had also, you know, an optical table and all that. So, the ground floor of the Raman Building was occupied like that. Soon, we started accommodating some environmental biology people there. And then the lady who shifted later on, moved to Bose Institute, Srimanti Sarkar. Then we moved to the first floor and other people also had labs there. So, most of the chemistry physics laboratories were there in the Raman Building. And then in the JC Bose Building, we started to have some labs on the ground floor. Prashant Upadhyay joined.

And then next to the JC Bose Building was the LEL Building, the old LEL. These names are all from the animal and fishery sciences or BCKV. We again reconstructed, remodeled it. And we started a new experiment of having some eight biology faculty members in the same area, sharing their common research facilities, like Jayasree Das Sarma, like Partho Protim Roy, like Shankar Maiti, like Chanchal Dasgupta, like Tapas Kumar Sengupta and so on. Then the theoretical physicists had their offices there. So, we soon became almost 50-60 faculty members.

But this campus was still being built. Now, as I said, this is already 2009. We have already spent three years of our time. And then in this campus area, there were a few buildings left over. They didn't demolish them. We also didn't want to demolish them. We reconstructed them. And now you can see them. Just behind the guest house is the Polymer Research Center. Priyadarshi is there and Raja Shanmugam is there. And then there's an Advanced Materials Laboratory, which is next door in the corner. Earlier, Sayan Bhattacharya was there, but he has moved out, I think. But then Soumyajit is there.

And then we created a seismic observatory towards gate number seven under Supriyo Mitra. It's still there. There's the equipment to check, because this is also an earthquake zone. And we wanted to connect to the Bakreswar Helium facility here. Because there's a correlation between earthquakes and the proliferation of Helium in Bakreswar.So, we want to study that. It's an inter-institutional program. And then there were two other buildings. One went to Radio Chemistry in Geology, Somnath Dasgupta and others, and the other to an environmental lab facility.

### SS: Is this towards the Kalimandir?

**SDG:** Towards the Kalimandir, yes. So these five buildings were there. But then soon again, we were short of space. Architectural modeling was done on the campus. Your hostel buildings had started to come up, but we needed space for the faculty. So we created the prefabricated structure buildings. And your hospital facilities are there. Gautam Dev Mukherjee moved his high pressure laboratory there. Jayasree had her biology lab there. So things were moving and were increasing. I think by the time I left, it was in September 2011, we already had close to 80 faculty members.

And one thing I am very happy to tell you, that though by my narration, you would have got an understanding that we were working against many odds in terms of space, in terms of facilities, but let's say we were very productive at that time, if you look at our publication record during that time. So, I state that concrete alone does not make good research. I mean, good research has to be done by the will of the people and the extent to which they put their mind to it and having very competent faculty. Most of them came after postdoctoral experiences, either abroad or in India, mostly abroad, after their doctoral thesis. And so, we had a very good set of faculty members. And J.C. Bose had two huge lecture hall auditoriums. I mean, each could hold at least 100 students. At that time, our intake was increasing. So, in the first year in the B.S.- M.S. program, the student intake was about 40, then it increased up to 100 maybe. And so, but then, as I said that the construction started and it was time for me to leave. Now you ask me, how do I feel after coming back? I feel very gratified.

I feel very happy that we chose this campus for one rupee, as I said. And it's a beautiful campus. It's very green, as you can see, with lots of trees, lots of flowers. And the swimming


**FIG 2: Sushanta Dattagupta carried out his doctoral research work at Brookhaven National Laboratory between 1969 and 1973, under Martin Blume.**

pool here, there are many sports facilities. And of course, the laboratory facilities are there. And so, facility wise, one cannot grumble, one cannot complain. It's sort of very gratifying that we moved here, especially also, see, as I said, it's less than 20 years. But maybe because the All-India Institute of Medical Sciences has come up, the roads have improved enormously. And by the end of 20 years, I think it will take you less than an hour to get here from the airport. So, if you compare, let's say, with Indian Institute of Science, and the time of journey it takes from the airport to Indian Institute of Science, that's actually much more than what it would be here in just about a year's time after the Kalyani Expressway is built up. And if they can solve the National Highway 34 problem near the Amdanga area, then going to the airport will not take you more than an hour.

And the proximity of Kalyani University, which is a very good state university nearby, and then the WBUT, the West Bengal University of Technology just has got a new name now, Maulana Abul Kalam Azad University of Technology, which has come near the campus. Then Netaji Subhash University is supposed to come. And with the Old River Research Institute here, we had a kind of a hub of education, which was the original vision that I shared with Buddhadev Babu when we got land here. So, it's very gratifying for me to come back and interact with students here and see how the campus has come up.

### SS: After leaving IISER Kolkata, you've been associated with Visva-Bharati University. How would you describe the difference between the university system - particularly Visva-Bharati - and an institution like IISER Kolkata?

**SDG:** There's a big difference. A university system like Visva-Bharati caters to all disciplines - not just science. In Visva-Bharati, the two most prominent departments are Kala Bhavana (Fine Arts) and Sangit Bhavana (Music). Another significant distinction is that Visva-Bharati integrates schooling into its system, a legacy from Rabindranath Tagore. It has pathshalas - like Ananda Pathshala, Santosh Pathshala, and schools like Patha Bhavana and Siksha Satra in Sriniketan. This integration of primary and secondary education within a university system is quite unique in India.

Furthermore, Visva-Bharati offers philosophy and comparative religion, various languages (including Chinese, Japanese, Arabic, Farsi, Indo-Tibetan Studies), and also runs a massive rural reconstruction program called Palli Sangathan in Sriniketan. There's Siksha Bhavana for science, Vidya Bhavana for humanities, and Bhasha Bhavana for languages. By contrast, IISER is the Indian Institute of Science Education and Research - it's purely focused on basic science education and research.

### SS: And how do the IISERs compare with the IITs?

**SDG:** IISER is also very different from the IIT system, which primarily caters to engineering and applied sciences. Back then, we observed a trend - bright students were moving away from basic sciences, often opting for engineering through IITs or, later, NITs. Our aim with IISER was to retain scientific talent in India and in basic science, specifically. We wanted to make science education attractive and integrated, so that students didn't feel the need to leave it behind after school.

### SS: How did that influence the conception of the BS-MS program of the IISERs?

**SDG:** That's a great question. You see, in our time, we had 11 years of schooling followed by 3 years of B.Sc., totaling 14 years before entering M.Sc. Higher secondary ended at class 11 back then. For your generation, it's 12 years now. But here's the issue: much of what was earlier taught in first-year B.Sc. got pushed into the last two years of school, syllabus-wise. But we didn't have enough qualified teachers in the school system to handle advanced science topics effectively. So. what happened was repetition - the same things taught again in B.Sc., which affected depth. Now it's 12 + 3, totaling 15 years, but content-wise it's scattered and not necessarily deeper.

### SS: So how did IISER resolve that?

**FIG 3**: Prof. Dattagupta delivering the Annual Oration 2025 of the West Bengal Academy of Science & Technology. Prof Dattagupta talked about the historic and scientific significance of the seminal letter sent by Indian physicist Satyendra Nath Bose to Albert Einstein in 1924.

**SDG:** We felt that the conventional 3-year B.Sc. plus the 2-year M.Sc. (3+2) model wasn't ideal. Everything could be covered in 4 years, and we wanted students to experience research. So, we designed a 5-year Integrated B.Sc.-M.Sc. program, where the final year would be research-focused, like an M.Sc. by thesis. This also helped phase out the old M.Phil. system. By the end of five years, students like you would not only have had a robust science education but also gained research experience, maybe even a publication. From the third year onwards, we encouraged research projects - both within India and abroad.

**SS: That must be quite different from a traditional university model.**

**SDG:** Absolutely. Universities like Visva-Bharati follow a more segmented discipline structure, whereas IISER promotes interdisciplinary science from day one. In the first two years at IISER, students were taught all major science subjects - physics, chemistry, biology, mathematics, and even computer science and earth science. The idea was to broaden scientific thinking before specialization.

In fact, initially, we even considered admitting only those students who had studied mathematics in school, to ensure a stronger foundation across the sciences. Students without mathematics were not encouraged to join initially. I don't know now what's happening. But there were some students who never had biology. But there are instances here where a student after doing biology in the first two years had got shifted or drifted to biology.

**SS: I actually know of two such instances. One of them is a member of InScight, she's an alumnus now. She didn't have biology in 11th and 12th and didn't want to do it. She studied biology in the first two years because it was compulsory, but she ended up obtaining an MS in biology.**

**SDG:** Ujani was in the first batch and she's another example of that, had a PhD in biology from Cornell and she is now in the faculty somewhere in biology. So, here are instances of that also. I'm very happy about that kind of interdisciplinary approach that we could instill in the students there and you are now saying that that has continued which is a very gratifying thing which is one of the aims and objectives of IISER.

By the way, life science started as an interdisciplinary subject - we branched off into different departments unfortunately, but it is very interdisciplinary and especially these days, when focus is very much on biological systems and material systems, you need interdisciplinary approaches of mathematics, chemistry and physics. So that way we feel that IISER was a very good experiment. Anyway, Visva-Bharati is another model.

Even within the university system Visva-Bharati from the Tagorean idea is a very different kind of a model. It's a unique model. I've already mentioned about the fact that the schools were part and parcel, the schools were imbibed within the university system. That's very different from other central universities like let's say JNU or Hyderabad University where I have served also. So that way, I hope I have answered your question about the difference between Visva-Bharati and IISER. Both are two different, both are very good experiences.

**SS: Do you see yourself more as a scientist or as a teacher?**

**SDG:** I would say teacher and a researcher, in that order. Because that's what I enjoy doing - teaching with research. I think teaching and research are two sides of the same coin. One cannot do without the other and in fact through classroom activities you get many new ideas of research also.

I can give you many examples from the history of development of physics where such things have happened. Because research is something that lies within yourself and maybe with some collaboration with some other colleagues but when you teach, you interface with a large number of students, you make eye contact, you sit with them over tea and then discuss even outside classes. So that's the part I enjoy most.

There can be, I believe in IISER also, there can be instances, there can be some people who are great teachers but research-

FIG 4: After leaving Carnegie-Mellon University, Sushanta Dattagupta worked as a post-doctoral researcher at University of Albera in Canada for a year.

wise they may not be the first options for the students. Similarly, there can be people who are doing fantastic research if you join them, it's a different ballgame but in classrooms they might not be the best teachers chosen for. So, my philosophy is that you have to be both if you want to be in IISER. If you only want to do research and write papers then you can be in a research laboratory. There are many CSIR labs, DST labs etc. – Tata Institute, where you don't have to do much teaching.

Your primary condition of even employment is that you're here to train students through teaching. At the same time, you also have to do research. So, I think that if your focus is only on research then IISER is not your place. If your focus is only on teaching also and not writing anything or doing much research then you're also a misfit here. So, you have to have a combination of both and this is the model I personally like very much. Even at this age I'm still productive in research. I write five to six papers a year in international journals. I even wrote some single author papers in the last three or four years in the physical review. Therefore, that part is there.

At the same time I feel that I must be able to translate my even physical review level research into a classroom teaching either for MSc students or even PhD students and even go to undergraduate level because that's the hardest part to teach because when you come fresh from school and your mind is keen to get into new ideas, stir up the class with questions and so that is also something I enjoy very much.

**SS: One of the goals of the IISER system was to retain bright minds in basic sciences. Can you comment on how studying basic science actually helps students in their career? Students like me who have obtained their BS-MS degree and want to pursue academia have to constantly worry about certain questions: What is the employment status after BS-MS? How about after a PhD? Some people say that basic science is saturated.**

**Others say that while an engineer will always find employment, a student of science has to wait until they become a scientist in order to get a proper job - and even that is on God's grace. What's your opinion on this?**

**SDG:** Okay, I appreciate the question. Let me say this first - You have to do what makes you happy, what brings you peace, and what makes you feel that you are your own person. You hold your own destiny in your hands. In a government system or industrial job, you might often be working to fulfill someone else's vision, climbing hierarchies, fulfilling institutional mandates. But one of the main reasons many of us chose academia is because we value academic freedom. While I admit that this freedom is slowly eroding, it still exists. So, first - do what makes you happy, not what others expect of you.

Secondly, let me talk about the societal aspect. Recently, I was teaching as a guest teacher in a school in Durgapur. The students were bright, and I enjoyed the interaction. But soon they began opening up. They told me horror stories - from class 5 or 6 onwards, they are pushed into private tuitions and coaching classes. It's quite traumatic. This is a new phenomenon, especially in townships like Durgapur, Jamshedpur, Rourkela. Parents are often part of nuclear families, and in the evenings, they have nothing else but to focus on but their children's academic performance. It's led to a system where coaching culture has become the new normal. Places like Kota have institutionalized this pressure.

This - what you're describing - is not just about science vs. engineering. It's about a deep-rooted societal insecurity: "What will my son or daughter do?", "Will they earn enough?", "Can they support us?". And there's a gender bias too - people often think, "My son will support the family; my daughter will get married." These are toxic ideas, but they're still very much present. So, if students fall victim to these insecurities, it's a problem. And sadly, this insecurity is pervasive in middle-class India today.

FIG 5: From 1981 to 1986, Sushanta Dattagupta taught as a Reader at the School of Physics in University of Hyderabad.

**SS: It is often said that it is easier to get a job in engineering that in science. What do you think of that?**

**SDG:** Let me give you a counterexample. Take Prasanta Chandra Mahalanobis, who started the Indian Statistical Institute (ISI). They run a B.Stat and M.Stat program that is phenomenal. If a student from ISI combines that with even basic business knowledge, they might end up earning more than an average IIT graduate. People just don't know about these opportunities. Or take mathematics - people think there's no future in it. But if you study math seriously, you can go into economics, data science, AI, finance, or modelling. You can enter banking, research, analytics, and so many other fields. So this idea that only engineering gives jobs is deeply flawed. There are plenty of opportunities in science - you just have to know how to navigate them.

Bottom line: this belief comes from middle-class insecurity, not from reality. That's why, Swarnendu, the very fact that you've left home, stayed in a hostel, and are thinking independently is already a big step. Now is the time to free yourself from societal pressure and follow what you truly love.

**SS: That is certainly encouraging, but the issue of funding remains, especially for those who are not yet in institutionalized research.**

**SDG:** I agree that there are irritating issues. I believe that Bengal doesn't have too many possibilities today and people want to leave, people find things elsewhere. Yet Bengalis, I know, don't want to leave this state. The cultural bonds are so strong. So, there's a dichotomy here and you're caught in that.

I agree with that. But earlier, you know, we went abroad even for graduate school etc. leaving our family. They were crying and all that sort of thing. But having done that, you feel happy. The world is becoming smaller and there are many possibilities. So, think of those possibilities. Don't feel that you have to be cocooned in Bengal, as a Bengali I'm saying.

And if you don't have that feeling, then you will find that there are many possibilities. At the same time, it is possible that today's climate is not really healthy for science. This is something that we don't want to get into in this discussion in detail. This is my feeling But what can you do? It is not in your hand. You can, of course, have a certain hand that you have voting power. But other than that, you have very limited ability to change the system. But nobody else can change you.

**SS: Do you believe in the brain drain concept?**

**SDG:** I don't believe in it because the world is one world. This did not happen in our time. Today there are a lot of students going to Korea, and a lot of students going to Singapore, Malaysia. This didn't happen during our time. So there are possibilities elsewhere, right? Israel, well, of course, Israel is now at war. But I'm saying many students are going to Israel, Weizmann Institute and other places.

So that didn't happen during our time. During our time, it was only the UK and America. Students are now going to Germany, France, and Russia. So I think things are changing also. So now brain drain, you're talking about, possibly there is a brain drain outside, away from Bengal. But I'm hopeful that things will change.

**SS: Well, the issue often is that people go elsewhere because there aren't too many quality opportunities here. And very often, if such people become successful outside, they do not feel the need to come back to the country. It almost feels like had they had opportunities to become succesful here itself, it would be a gain for this country as well.**

**SDG:** Yeah, one thing I feel is Swarnendu, I think institutes like this should also be international. There should be students not just from all parts of India but also from outside. This is the strength of the Western universities like Oxford, Cambridge or American universities. Vast number of students come from outside. So you also have a cultural mix. You should not be just soaked into one culture and so if you are very multidimensional, then maybe such concerns should be little less, what you are talking about.

**SS: But in India, everyone who has to join higher education, masters or PhD in a good place, as far as science is concerned, you have to clear JEST or JGEEBILS, NET, GATE and those are the only pathways you can achieve that. In**

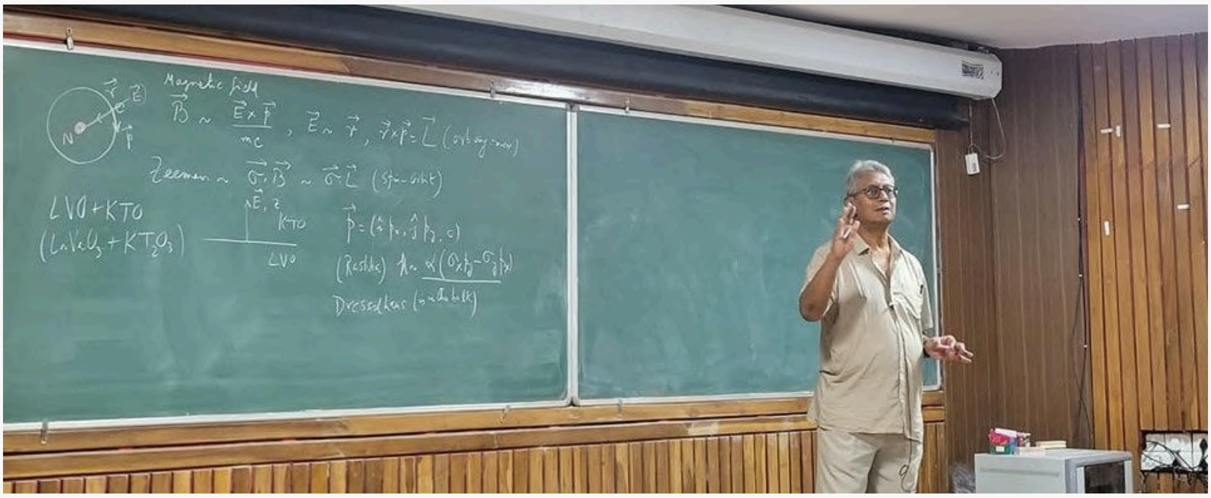

FIG 6: Sushanta Dattagupta delivering a series of lectures at the Indian Institute of Science Education and Research (IISER) Kolkata. He served as the founding director of IISER Kolkata from 2006 to 2011.

**international universities, you can just mail them or apply in a portal and if there is a possibility, they reply back to you. That doesn't happen in India.**

**SDG:** So Swarnendu, if you ask me as a private person, I do not believe in all this NET, GET etc. You know that I served Visva-Bharati. Rabindranath Tagore didn't go to school. Einstein didn't have a very fantastic record in schooling. So, these are mechanical things. Perhaps they came in because they had to uniformize or whatever, a PhD from one state was not the same as a PhD from another state. Traditionally in Bengal, University of Calcutta, not in your time maybe, but in our time, they were very conservative about giving marks.

So even 65% in physics honours was considered to be very good, not today maybe, but that is not the case let's say in another university which I'll not name. So maybe they had to uniformize, but I don't believe in these things. So, I think these are all mechanical things and really motivated students may be deterred from such mechanical things.

On a given day, you may not do well in a NET exam or GATE, but you are good. So why should the system lose you? So as a teacher, I would like to support such students, but as a system it's very difficult. So, I agree with you that when you are writing to professors abroad, they don't ask you whether you have cleared your NET, GATE and all that.

**SS: They only take interviews if they have a position and they try to understand if I can do it. If not, I know it or not. If I am able to do it, I think that should be adequate. If the teacher wants it, you want the teacher, the place administrator wants you and it's done.**

**SDG:** Yes, yes and I think that's the healthy system. We actually have got into an unhealthy system, very mechanical. I will give you an example.

Since you mentioned Visva-Bharati, have you heard of Ram Kinkar Baij? He was a sculptor. He's from Bankura, completely supposedly illiterate. Could he have become a professor in Visva Bharati by today's standards? He had not cleared NET. He used to stay in his own world, stay in his own fashion. He was a professor. Konika Bandyopadhyay was a professor. Did Konika Bandyopadhyay clear NET examination? So why do you have such things? J.C. Bose did not have to clear NET examination. By the way, they were all part of the teaching departments.

You were asking earlier about teaching and research. The fact that S. N. Bose could do this problem of how to count and have a new kind of statistics by saying that particles are indistinguishable, that happened because students were asking him, barraging him with questions. "Sir, this derivation of Planck law radiation is not very satisfactory, you know, you please explain." That is what drove him there. To answer the question in the class.

It was not just in Dhaka in 1924 when he wrote that letter to Einstein, but it started happening from 1920-21 onwards in University of Calcutta when he was teaching mathematics here. So it is because of the students asking him questions. The researcher J.C. Bose was teaching in Presidency College. So, examples galore where teaching and research in combination have produced this.

Here, after independence, we have separated our research institutions from the university system. Has that been good for us? We keep on asking why there are no Nobel Prizes from here? The answer is obvious, I think.

**SS: On to my next question. For the last several months, many international opportunities have become blocked. The US appears cutoff. UK says we don't have funding. many countries are at war. In this scenario, what is your suggestion? How should today's students make progress? Is doing a PhD in India a good choice? More specifically, how much of a difference does getting a degree from a good Western University make versus getting the degree from a good place in India?**

**SDG:** Let me answer the last part first. There are many counterexamples of students, who have done PhDs in our country, have done exceedingly well internationally also. I can give you some names also. So, I think again that distinction is immaterial. The first part is difficult for me to answer. Let me tell you my own experience with my two daughters.

My elder daughter Shahana, after schooling, did architecture from Delhi School of Planning and Architecture. Then she had some higher degrees in the U.S. and also she was working for a company. So, as an architect, she would have done very well.

She is very, very creative. She is very strong in mathematics also. But today, she is completely into Dhrupad music. So, one may think, ah, she has wasted her career. She could have become

**FIG** 7: Profs. Bernard C. Patten, Brian D. Fath, Sushanta Dattagupta, and Sudhendu Mandal during the inaugural functions of the International Conference on Environmental Biology and Ecologiacl Modelling, Visva-Bharati University, Santiniketan, India (Photo credit to Jana Debaldev).

a great architect, but she is in Dhrupad. I don't think like that - she is personally very happy with music – she has innumerable mentees all over the world - and I am extremely happy for her.

My younger daughter Sharmishtha did chemistry from St. Stephen's College, Delhi. And then did an M.Tech program from IIT Bombay in biotechnology. Then did a PhD in deep sea biology in Pennsylvania State University. Eventually had a position, faculty position, in geobiology in the Courant Center of Excellence in Geo-biology in Gottingen University. But she gave up everything and she is now a life's coach.

What is that? Basically, she talks to people about happiness in life, going mountaineering, going to yoga, going to, you know, practising spiritualism and traditional knowledge, ecology and all that. And she lives mostly in India, in Himachal now. And also works with Adivasi women near Shantiniketan in Bolpur, where I stay.

### SS: And that's very fulfilling for you, I guess.

**SDG:** Fulfilling for her also. So, what more does one want in life, I am saying. She drives all the way in her Alto Maruti car, all the way from Himachal to Shantiniketan, Bolpur, where I stay in the house designed by Shahana, who is an architect. So, they are not in any kind of traditional mold anymore. This is very different from our days. Since you are asking me, it is a very difficult question to answer now.

Because in our days we came from middle class families - one track minded. You have to do physics, then you have to do this, do PhD, do post-doc, then see where you get the faculty position. So, these kids are now able to do many other things. So, Swarnendu, the reason it is difficult is that our days and your days are very different now. So, we should not bias you from our kinds of experiences. And we should also adapt to your needs.

The fact that you are happy with doing what you are doing is the most important. Gone are the days where you would stay at home, looking after parents in the old days, etc. But, you know, that also made parents dependent, your dependent, and your freedom curtailed. But now, even staying away, you can do a lot for your parents. I don't think that that concern is not there anymore because connectivity has also increased, you know. You can travel much faster today compared to our days. First time I went inside a plane was when I went to the US for my PhD studies. But these days, you guys are travelling all the time.

### SS: This question is not to the researcher Sushanta Dattagupta, but primarily to the teacher Sushanta Dattagupta and the person Sushanta Dattagupta. Do you feel today's students have forgotten to talk, have forgotten the meaning of friendship. Today's students, though more alert, frequently fall prey to substance abuse.

### After graduating, they forget the friends they made there. It feels like we talk only when we absolutely need to, and not for the sake of relationships. Even though many of my school friends are in Kolkata, we rarely meet. Do you have any comments on this trend?

**SDG:** I think this is not a good trend. In fact, when COVID happened, we went into a system of virtual classes. I think that's disastrous. Unless you have eye contact with the teacher, and also reversely with the students by the teacher, it's not a very effective communication. That's number one. So, what you are saying is that today, most of the time, with earplugs, listening to mobile phones, maybe some music, some recording, you have very little time for even Adda, as you mentioned.

### SS: We all have problems - academic problems, financial problems, problems at home, etc. But we don't have close friends to talk to about them. It seems like people are insecure about opening up in front of others about their vulnerabilities. How does one cope with that?

**SDG:** I don't really know. One thing is sports facilities. Like, you know, if you are feeling bored, go play basketball. Go play volleyball. Chat with the guys. This campus is fantastic for that. Go and have a swim. Do that. Or go cycling in the campus. Watch the birds. Watch the many varieties of flowers here, nature. Getting hooked on the mobile phone is a scourge, I think.

### SS: How are Tagore's works related to science?

**FIG** 8: At the release of a book on the doyen of Rabindrasangeet: Shailajaranjan Majumdar, on his 125th birth anniversary, at the Lipika auditorium of Visva-Bharati. Standing by his side is Dr. Shruti Bandyopadhyay, Principal, Sangit Bhavana.

**SDG:** Fantastic. A lot of people don't know that Tagore was very interested in mathematics. His eldest brother more so.

**SS: Are you talking about Dwijendranath?**

**SDG:** Yes. He was very good at maths. And he was the one who was a nature lover. Birds and all that. So, he imbibed that. Tagore actually got a lot of things from his brothers and combined them into the genius that he was.

The first article that Rabindranath published in Tattvabodhini Patrika at the age of 12 was on astronomy. So, then, you know, Tagore is quite interesting. Tagore was a great friend of J.C. Bose. Around 1900, they were writing lots of letters. Bose Institute has come up with two volumes. In which these letters are there. But, if you look at them, Tagore was trying to understand what Bose was doing. And, Bose was actually propagating Tagore's works in the western world also. Translating them into English.

So, science was very much in Tagore's mind. Eventually, he went and met Einstein. Five times. Between 1926 and 1930. Then, Heisenberg came in 1929 to Jorasanko to have tea with him. He went to Darjeeling on the way. He stopped by and had tea with Tagore. And, he wanted to understand about Upanishad and the idea of how you learn things from nature. And, the fact that Upanishad, this is what he says to J.C. Bose. Upanishad taught us that everything, even which you think is immobile, actually vibrates with life. He basically talked about atoms and molecules, even in trees and even in concrete. And so, Heisenberg writes about that to his daughter. Then, Sommerfeld went to Shantiniketan in 1928.

It is Sommerfeld who during Tagore's visit to Germany introduced Meghnad Saha to Tagore. Tagore talks about Meghnad Saha's work in Bishwa Parichay, which he wrote between 1934 and 1937. Bishwa Parichay has various sections - full of various scientific concepts and much of it has to do with radiation and *Alo* (light). And what is the meaning of *Alo*? And *Alo*, as you know, is a basic aspect of science. So, Tagore, I think, had a scientific mind. It's just that he is a great philosopher.

**SS: It has been very nice talking to you, sir. One last question, what is your advice to the students, and maybe particularly to the outgoing students?**

**SDG:** Be happy, be on your own and be responsible to your surroundings. Worry about the fact that we have done big damage to ecology in the name of development. If you look after your health and look after your health means that you have to do physical exercise and look after your diet and also be happy. So, mental peace is the most important thing in life and that is what you should have. And finally, as you said, and I'm unhappy to hear this, you must have a lot of friends and have a lot of *Adda*.

**SS: Thank you, sir.**

**FIG 9: In 2011, Sushanta Dattagupta was appointed as the Vice-chancellor of Visva-Bharati university. He served in that role till 2016.**

# The Chemical Ballet: How Volatiles Orchestrate Pest and Predator Behaviour


## Sayantani Nath (Interactions Lab, Department of Biological Sciences, IISER Kolkata)



**What if plants could talk? Not with words-but with scents.** Plants release special chemicals called VOCs to call for help, warn their neighbors, confuse attackers, and even sabotage rivals. Dive into this fascinating world with Sayantani Nath where leaves cry for help, roots make alliances, and researchers uncover nature's invisible language-one scent at a time.


*Also available online, at scicomm.iiserkol.ac.in*


**REVIEWED BY**
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**CATEGORY**
Biology

**Sayantani Nath** is a budding researcher with a background in entomology and plant-insect interactions, driven by curiosity and a love for understanding nature's complexities. Beyond the lab, she finds joy in exploring new places and cultures; travelling fuels her creativity and deepens her appreciation for biodiversity across ecosystems.

Plants are much more than the silent, passive participants in the complex and grand symphony of life. When trapped and confronted by noxious enemies, they can come up with an incredible range of strategies for survival, thriving, and fighting back. Research has shown that plants can rapidly and accurately recognise their attackers, relaying this information to beneficial parasitic wasps [1]—a finding with profound implications for enhancing integrated pest management programs. The quintessence of these strategies lies in their capacity to release volatile organic compounds (VOCs) that act as invisible communication agents, free-floating in the air. Similarly, the sesquiterpene (E)-β-caryophyllene [2] has been identified as an attractant for entomopathogenic nematodes to maize roots below ground. These compounds narrate tales of survival that are included in the stories of multitrophic interactions that, among themselves, maintain equilibrium within ecosystems.

## A Hidden Symphony

Imagine a forest where the air hums with the quiet rustling of leaves—plants engaging in whispered but potent dialogues. They are the green maestros conducting an orchestra, playing their music of survival using VOCs [3]. These aerosol signals are emitted by plants in response to biotic stresses, such as herbivore feeding, pathogen attack, or competition by neighbouring plants, as well as abiotic stressors like drought and temperature variations that play key roles in attracting pollinators, deterring herbivores, and signalling threats. We often fail to recognise that these VOCs are the plants' sophisticated method of communication. They can be used to warn other individuals, whether it be a friend or foe. Every note in this silent symphony is significant. VOCs emitted by plants rise above their seeming immobility to become actors in this silent drama of survival.

## Signals of Distress

An injured leaf, when chomped by the mandibles of an herbivore, gets transformed into a secret arena of combat. These compounds don't just linger in the air—they travel and interact with other organisms. We do not see the affected plant cry. Rather, it sends a SOS into the atmosphere—the VOCs. They are transported through the canopy, connecting with nearby plants to convey the looming bad news. This surveillance enables neighbouring plants to prepare themselves by synthesising toxins or making their physical defences more fortified. But the story doesn't end here. Plants also use VOCs to assert dominance in the competition for space and resources. Some species are known to produce compounds known as allelochemicals that limit seed germination of the adjacent plants, preventing hostile neighbours from flourishing. This symbiosis of cooperation and conflict in plant communities drives the complexity of VOC-mediated interactions.

## The Dance with Herbivores

As herbivores take the stage, the story ramps up. However, it's no easy feat for a voracious, hungry insect to find its next target. Plants, equipped with their VOC defences, shroud themselves in

**FIG** 1: This illustration depicts a plant emitting diverse **volatile organic compounds (VOCs)** in response to herbivory. These volatiles travel through the air, attracting **insect predators and parasitoids** (like wasps and ants) that target herbivores such as **caterpillars** and **beetles** feeding on the plant. This highlights an indirect defense strategy where VOCs serve as airborne signals to recruit natural enemies, enhancing the plant's protection.

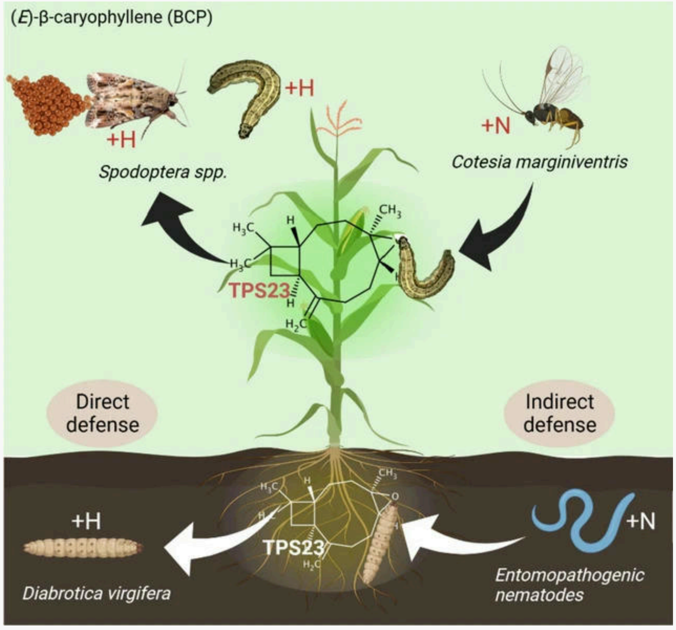


**FIG** 2: Pleiotropic functions of (E)-β-caryophyllene in maize plants and several interacting organisms, including leaf herbivore (*Spodoptera littoralis*) larval parasitoid (*Cotesia marginiventris*), western corn rootworm (*Diabrotica virgifera*) and entomopathogenic nematode (*Heterorhabditis megidis*). (Munawar *et al.,* 2023)

"chemical invisibility," concealing the cues that herbivores depend on to find their food sources. This deception bewilders the attackers, causing them to overlook their hosts. The environment of the plant transforms into a fortress, making potential feeders stumble upon a bubble of chemical deterrents. However, plants aren't just trying to protect themselves; they have some clever tricks up their sleeves. Some VOCs mimic odours associated with dangerous and non-host plants, which the herbivores quickly learn to avoid. Despite this, in some instances, these compounds can even trap herbivores or lure them to locations where they are unlikely to survive.

## Rallying Reinforcements

The herbivore-induced plant volatiles (HIPVs) serve as a chemical "alarm" that attracts the natural enemies of herbivores, such as their predators and parasitoids. Herbivory sets off a signal transduction pathway inside the plant, resulting in the biosynthesis and release of VOCs such as green leaf volatiles (GLVs), jasmonates, and terpenoids [4], that lure in parasitoids that attack aphids or larvae feeding on the plant. They are the plant's unwitting natural enemies, but allies that turn against the parasite.

## Volatiles Across Trophic Levels

VOCs feed into the web of interactions much further afield from that immediate plant-herbivore-predator triad. Beneath the soil, a new play commences. Roots release VOCs that shape the microbial community in the rhizosphere [5], selectively attracting beneficial microbes such as nitrogen-fixing bacteria and mycorrhizal fungi. These friendly microbe allies do the work of making nutrients available and plant growth, which makes plants grow. VOCs act to suppress the development or infection of a wide range of harmful pathogens, at the same time, conserving plant health. In addition, VOC-driven interaction drives the functionality of nutrient cycling (promoting organic matter decomposition and nutrient release back into soil) as well. That belowground network of connections allows VOCs to help the plant out above ground and even below the soil, where unseen sidekicks are doing their thing to keep plants alive.

## Experimental Insights

VOCs have long since opened a new area of research, unlocking the hidden language of plants and deeper into scientific intrigue. It is thanks to the introduction of modern and sophisticated instrumental analytical techniques like Gas Chromatography-Mass Spectrometry (GC-MS) and complex olfactometric systems that we are now able to unravel the underlying chemical composition of VOC blends with amazing accuracy. GC-MS helps in the separation and identification of VOCs in a mixture and helps decode complex VOC blends by pinpointing individual components, linking chemical identity with biological activity such as insect attraction or repulsion. These technologies have cracked the code not only on how plants can communicate with each other and other members of their community, but also how they defend themselves from herbivore attack, appeal to organisms and even manipulate their environment using complex strategies.

## Field Applications

VOC research has practically applicable results as exhilarating as they are profound. Plants communicate with chemical signals that serve as cues about the presence of natural enemies, and synthetic VOCs just sort of mimic these signals to disperse biological controls for crop protection in agricultural fields. For instance, synthetic terpenes that are modelled after natural HIPVs are being tested to attract beneficial insects directly to threatened crops [6].

VOC-based strategies are an environmentally benign alternative to the currently used chemical pesticides with low environmental and health risks. While broad-spectrum pesticides kill both the pest and some pests' natural enemies, along with other helpful organisms.

## Implications for Ecosystem Stability

VOCs' significance in preserving ecological balance is highlighted by their function in mediating multitrophic interactions. These relationships maintain biodiversity, improve nutrient cycling, and control pest populations, all of which support ecosystem stability. However, these networks are in danger of becoming unstable due to disturbances

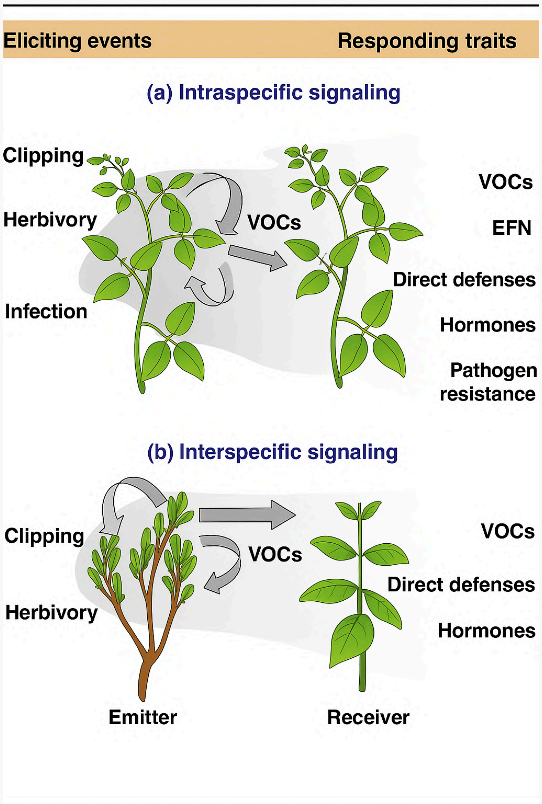


**FIG** 3: This diagram illustrates how volatile organic compounds (VOCs) mediate both **intraspecific** (within-species) and **interspecific** (between-species) signalling in plants. In response to cues like **clipping, herbivory, or infection**, emitter plants release VOCs. These volatiles trigger responses in neighbouring plants—such as direct defences, hormonal changes, the production of extrafloral nectar (EFN), and **enhanced pathogen resistance**—allowing them to prepare for potential threats preemptively. (Heil & Karban, 2009).

brought on by pollution, habitat loss, or climate change, which could have a domino effect on food security and biodiversity. Investigating the effects of global climate change on VOC emissions calls for immediate attention and action. Elevated atmospheric $CO_2$ levels, rising global temperatures, and shifting precipitation patterns are all known to influence the biosynthesis, release, and volatility of plant-emitted VOCs [7]. Moreover, air pollution, such as ozone or nitrogen oxides, can degrade or alter these VOCs, weakening their signalling effectiveness. This disruption can reduce pest control efficiency. These changes might then disturb the finely tuned multitrophic interactions that VOCs mediate—interactions between plants, insects, bacteria, and other organisms necessary for agricultural output and the balance of ecosystems.

The importance of comprehending and protecting these fragile networks is underscored by the fact that, for example, changed VOC emissions under changing climates may lessen their ability to draw in natural enemies or ward off pests, increasing ecological and agricultural vulnerabilities.

## Future Directions

As our understanding of volatile organic compounds (VOCs) deepens, new frontiers in plant science and agricultural innovation continue to beckon. Long acknowledged for their functions in plant defence, communication, and ecological interactions, VOCs are now central to innovative strategies aiming to revolutionise pest control, pollination, and soil health. The potential for using VOCs in agriculture is enormous and still mostly unrealised. We can create plant varieties that naturally draw pollinators and beneficial insects like parasitoids or predators while also discouraging herbivores and disease vectors by improving and modifying the volatile organic compounds (VOCs) in crops. By providing more ecologically friendly substitutes that complement natural systems, such tactics could drastically lessen our dependency on artificial chemical pesticides.

Another fascinating and fast advancing field of research is synthetic biology. Through genetic engineering, it is now possible to reprogram plants or associated microbes to produce specific, beneficial VOCs on demand. This innovation opens up the possibility of designing living systems tailored to address particular agricultural challenges—whether it be pest control, improved disease resistance, or enhanced nutrient uptake and cycling. For instance, while the induction of VOCs signals beneficial microbial colonisation could lead to more resilient plant-microbe interactions, the controlled release of repellent VOCs from engineered microbial communities in the rhizosphere could offer a new form of pest deterrent. By harmonising with ecological ideas and reducing environmental disturbance, these complex biological solutions have great potential to transform contemporary agriculture.

However, these advances must be considered within the broader context of a changing climate. Not only will knowledge of how climate-driven changes affect VOC dynamics help to forecast future ecological scenarios, but it will also enable the development of adaptive strategies protecting food production and biodiversity in a world fast changing.

As more and more plant-emitted volatiles are being explored, we find their central role in the complex chemical dance of nature. Plants use these molecules as their they choreograph complex ecological relationships, shaping interactions from insect behavior to microbial alliances. Deciphering this silent but significant communication helps us to design sustainable agricultural solutions to safeguard crops, improve ecosystem services, and lower our environmental impact. The hidden symphony of VOCs stands as a powerful testament to the ingenuity and resilience of plants, showcasing their extraordinary ability to adapt and thrive amid ever-evolving environmental challenges. As we continue to delve deeper into this field, we move closer to a future where agriculture and ecology are not in conflict but in concert, united by the invisible threads of chemical communication.

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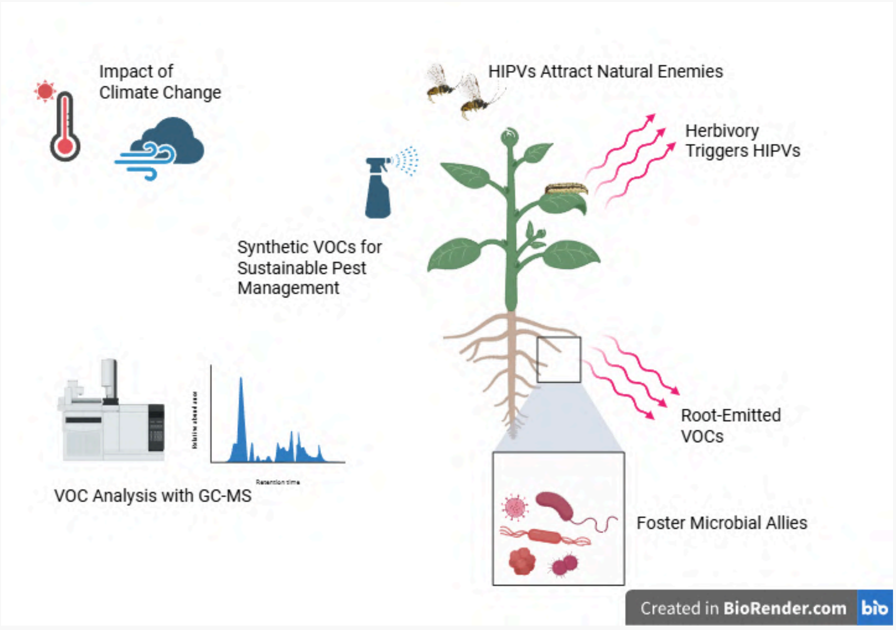


**FIG** 4: This figure illustrates how volatile organic compounds (VOCs) mediate plant interactions. Herbivory induces HIPVs that attract natural enemies. Root-emitted VOCs foster beneficial microbes. GC-MS helps identify VOCs. Synthetic VOCs support sustainable pest control. Climate change alters VOC emission patterns, potentially disrupting ecological functions and plant defence signalling networks.

# Cosmic music of the Sun: Rossby and other inertial modes

Suprabha Mukhopadhyay (Solar and Stellar Interiors Department, Max Planck Institute for Solar System Research, Göttingen, Germany)

Astrophysical bodies emit a certain kind of "music" in the form of inertial modes of various frequencies. This article explores the recerntly observed inertial modes of our Sun, going into what these waves can tell us about the behaviour of the Sun and how they can affect us.

*Also available online, at scicomm.iiserkol.ac.in*

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**CATEGORY**
Physics

**Suprabha Mukhopadhyay** is a physics enthusiast. He is interested in the physics of the Sun and is studying waves in the Sun for his PhD at Max Planck Institute for Solar System Research, Göttingen, Germany. Earlier, he studied the long-term modulation of solar activity during his MS thesis at CESSI, IISER, Kolkata. Apart from Physics, he likes coding. In his free time, he does not miss any opportunity to travel and explore different places.

Did you know that the same kind of waves, which help shape Earth's weather patterns, may also ripple through the Sun's atmosphere? Rossby waves are a special class of inertial waves which are restored by the Coriolis force in a rotating body [1,2]. Rossby waves are particularly caused by a rotating sphere's special property that the Coriolis force's tangential component changes with latitude. They are a cornerstone in Earth's climate science [3,4]. But what happens when we look for these waves on our star? Imagine the Sun as a musical instrument where waves resonate differently within its rotating plasma. Researchers only recently attempted to observe such inertial waves on the Sun [5]. Why do we care about these waves in the Sun? Because they help us understand how the Sun spins, how it ages, how the plasma inside the Sun behaves, and even how it influences space weather — all things that affect our life on Earth in ways we're only beginning to understand! In this article, I explore how we can observe solar inertial modes and why they could not be identified in the Sun earlier. I also discuss their importance for the Sun, the fundamental physics of these modes and the future of this field of research.

## How do we observe solar inertial modes?

When the rotationally driven inertial waves are trapped inside a closed system like a spherical shell, they are called inertial modes. To understand why observing inertial modes on the Sun took so long, we must consider how they behave in rotating systems.

Inertial modes oscillate with periods set by the rotation rate of the system. Any inertial oscillations must have their frequency ranging from $-2\Omega_0$ to $2\Omega_0$ for a system rotating at an angular frequency $\Omega_0$ [2]. Now, consider the rotation rate of the Earth and the Sun. The Earth takes one day to complete one rotation, while the Sun takes about 27 days to complete a rotation. The period of inertial oscillations in the Sun will be much larger than in a fast-rotating body like the Earth. Hence, we need long-term, continuous observations of the flows on the solar surface to identify inertial oscillations in the Sun. This has been made possible with recent high-resolution observations of the space-based telescope Helioseismic and Magnetic Imager (HMI) from the Solar Dynamics Observatory (SDO), a spacecraft of NASA. First, the classical Rossby modes were identified using the Fourier transformation in longitude and time at each latitude of the solar surface flows obtained using this telescope [5]. The Fourier transformation in longitude fixes the azimuthal wavenumber m, which is the number of wavelengths around the equator for a mode. Then the first observations were combined with the observations of the Michelson Doppler Imager (MDI) from the Solar and Heliospheric Observatory (SOHO), a spacecraft of the European Space Agency (ESA), using a technique called time-distance helioseismology [6].

Later, many other inertial modes were observed on the Sun using observations from HMI and the Global Oscillation Network Group (GONG) from the National Solar Observatory (NSO), headquartered in Boulder, USA [7]. Fig. 1 shows the eigenmodes of the high-latitude inertial mode and the classical equatorial Rossby mode adapted from [7]. The high-

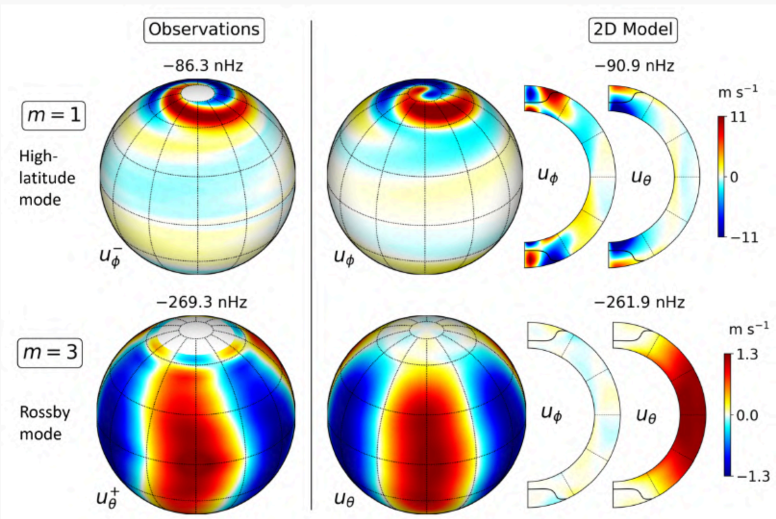


**FIG** 1: Eigenmodes of the high-latitude inertial mode and the equatorial Rossby modes from HMI observations and eigenmode calculations, adapted from [7]. The eigenmode calculations use the 2D model in the solar convection zone, as explained in [8]. Latitudinal and longitudinal velocities are represented by $U_\theta$ and $U_\varphi$, respectively. Azimuthal wavenumber, denoted by m, is the number of wavelengths around the equator for a mode. +/- indicates that the observed eigenfunctions are north-south symmetric or antisymmetric in that specific component.

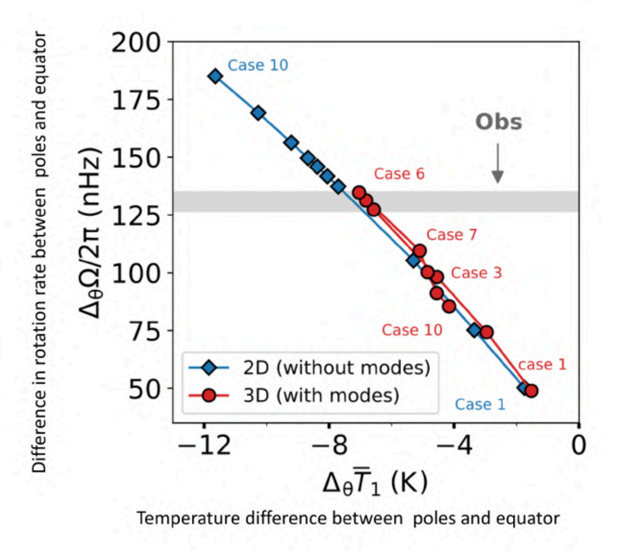


**FIG** 2: Plot of the difference between the rotation rates at equator and poles against the same for temperature for 2D axisymmetric simulations and 3D simulations with high-latitude modes for different deviations from the background adiabatic temperature gradient (adapted from [17]). The deviations increase with the case numbers. The grey slice shows the range of differences in the rotation rate observed in the Sun.

latitude inertial mode with azimuthal wavenumber m = 1 has the highest power in the observations, and it was found to be driven by the temperature difference between the poles and the equator of the Sun due to the difference in the rotation rates [7,8]. This is termed baroclinic instability. The unstable high-latitude mode has recently been identified in daily-cadence solar Doppler Grams, including the ones from the Mount Wilson Observatory (MWO), at Los Angeles, USA, since 1967 [9]. Fig. 1 compares the observed eigenmodes with the 2-dimensional eigenmode computations of [8]. Scientists have recently compiled a review on the observations and modelling of different classes of solar inertial modes [10], which can help one get a nice overview of the recent advances in this field of research.

## Why are they important?

Rossby waves on the Earth are vital because they affect weather patterns on the Earth. Why would they be interesting in the Sun, given that there are no clouds, rain or floods in the Sun? In contrast to Earth, solar inertial modes can reveal secrets about its hidden internal dynamics. Helioseismology using pressure modes can tell us a lot about the solar interior [11-12]. But pressure modes can't tell us much about viscosity, heat flow, or latitudinal temperature variations in the interior of the Sun. These quantities are essential for global solar simulations as well as modelling and predicting the solar magnetic activity. In particular, there exists disagreement between the velocity amplitudes in simulations and observations, termed the convective conundrum [13-15]. The inertial modes have been demonstrated to be sensitive to many parameters, which are not well-constrained yet [7,8,16]. Thus, inertial modes can aid in the Sun's diagnostics and help solve the conundrum. Furthermore, unstable high-latitude inertial modes have also been found to play a dynamical role in the Sun by controlling the solar differential rotation [17]. Fig. 2 illustrates how these modes act like a feedback system, regulating the Sun's rotational and temperature differences across latitudes. The different cases have different degrees of convective instability, increasing with the case numbers, as described in [17]. In the absence of these modes, the difference between the rotation rates and temperatures at the poles and the equator can become much larger compared to the cases with the modes. In the presence of the modes, the differences are limited to a specific value, close to the observed difference in the rotation rate between the pole and the equator.

## The physics behind the inertial waves

For those interested in the physics, here's how scientists break it down mathematically, starting from the fundamental fluid dynamics. A fluid's spinning or swirling motions can be quantified as a quantity called vorticity. Inertial modes can be described as waves of this quantity called vorticity [2]. Hence, analysing the vorticity budgets of the inertial modes is instrumental to understanding their physics, as done in [18]. Starting from the equation for the conservation of momentum of the fluid, we can obtain the equation for vorticity by taking a curl, which helps get the system's spin from velocity. To analyse how the different physical effects determine the frequency of the modes, we transform the equation of vorticity $\zeta$ (radial and z-components, where z-axis is along the axis of rotation) to the following form[18].

$$\omega\,|\zeta_r|^2 = \mathcal{G}_{\text{planetary}} + \mathcal{G}_{\text{comp}} + \mathcal{G}_{\text{other}}$$

$$\omega\,|\zeta_z|^2 = \mathcal{W}_{\text{comp}} + \mathcal{W}_{\text{topographic}} + \mathcal{W}_{\text{other}}$$

Here $\omega$ denotes the angular frequency of the mode studied. We decompose the vorticity equation into the different physical effects. The planetary $\beta$ effect (denoted by planetary) is caused by the latitudinal variation of the tangential component of the Coriolis force [2]. It is the primary driver of the Rossby modes. The compressional $\beta$ effect (denoted by comp) is caused by the change in background density when a fluid parcel moves along the radius [2]. It becomes essential only when there are radial motions associated with the mode. Finally, we also have the topographical $\beta$ effect (denoted by topographic) caused by trapping the fluid parcels in a spherical shell [1]. The sign of the terms in the above equations associated with these physical quantities determines the direction of propagation of the modes. This is because the frequency is multiplied by the absolute value of the different vorticity components, which is always a positive real number. Fig. 3 shows how the various physical effects determine the frequency of a mode by promoting their propagation either in the direction of rotation (prograde) or against the direction of rotation (retrograde). It shows the example of the high-frequency retrograde inertial mode discovered in

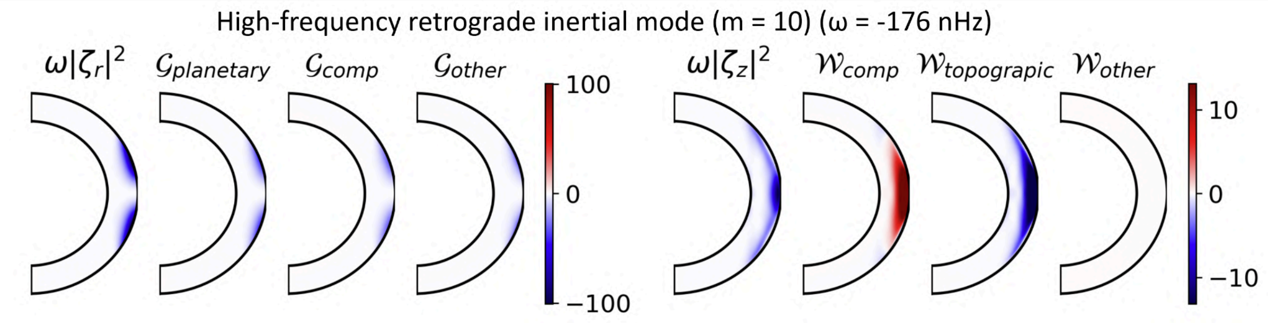


**FIG 3: Quantification of the relative importance of planetary $\beta$ effect, compressional $\beta$ effect (comp), topographical $\beta$ effect and other terms in the vorticity equation to determine the propagation and frequency of the high-frequency retrograde inertial mode with azimuthal wavenumber m = 10 (adapted from [18]). A negative quantity implies that the associated physical effect promotes propagation in the direction opposite to rotation. In contrast, a positive quantity implies that its physical effect promotes propagation in the direction of rotation.**

[19]. This is an interesting mode driven by the combined effects of planetary $\beta$ effect, compressional $\beta$ effect and topographical $\beta$ effect, as found recently [18]. The compressional $\beta$ effect drives it prograde, while the other physical effects compete to drive the mode retrograde. Furthermore, the importance of compressional $\beta$ effect due to the presence of radial motions in the inertial modes makes the inclusion of background density variations necessary while modelling the solar inertial modes, as found in [18]. This is in contrast to the inertial modes on the Earth, where the background density can be assumed to be constant because of slight variations. On the other hand, density drops off steeply with radius in the Sun.

## What does the future hold?

There are many aspects of developments in the modelling of inertial modes. The inertial modes are sensitive to different physical quantities in the solar interior. It will be fascinating if the inertial modes can precisely reveal these yet unknown physical quantities to help solve the convective conundrum. Apart from that, how the inertial modes affect or are affected by solar magnetic fields is not well understood. Also, we do not yet know how the solar inertial modes are affected by different layers of the Sun, like the radiative zone and the solar atmosphere. Furthermore, how the unstable high-latitude modes saturate is to be understood carefully, as their amplitude can not grow indefinitely over time. Many of these topics are actively explored at research institutes across the globe. As we unravel the Sun's hidden rhythms, we're not just doing solar science — we're playing catch-up with the universe's cosmic symphony. The future promises more discoveries, and maybe we'll soon predict solar storms even more accurately than we forecast monsoons.

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Prof. Mitra explains the phenomenon of zero shadow day to the introductory summer school students at the Inter-University Centre for Astronomy & Astrophysics (IUCAA). [Source: LIGO India Facebook page]

# Meet Prof. Sanjit Mitra, the Science Spokesperson of LIGO India


## Swarnendu Saha (IISER Kolkata)


*Ever wondered how a reluctant chemistry student becomes a gravitational wave pioneer?* Join Dr. Sanjit Mitra as he traces his accidental journey from Kolkata's B.Sc. classrooms to playing a leading role in India's endeavour in the cosmic detective work with LIGO, where mirrors detect ripples in spacetime thinner than a proton! He'll decode why three global detectors are essential to pinpoint colliding black holes and how LIGO-India could soon become one of the main players in this scene. But brace yourself: he also questions if our education system stifles more thinkers than it fuels—what do you think?

*Also available online, at scicomm.iiserkol.ac.in*

**SS: Welcome, sir. I am Swarnendu Saha from Team InScight, and today I have the privilege of engaging in a conversation with you to explore your journey and gain some insights that may guide us forward. We'd love to talk a bit about your academic background, your research, and, if possible, take just a little of your valuable time.**

**Let's begin with some basic questions.**

**Could you please tell us where you come from and walk us through your academic journey, starting from your early years?**

**How did you arrive at where you are today - what were the key steps or decisions along the way?**

**SM:** That's actually a long story! Initially, I wanted to pursue engineering. But back then, I barely knew any chemistry. So, the chances of getting into an engineering program were quite low. I thought, "Maybe I'll take a year, prepare well, and try again next time." This was during my Class 12 days - I passed school in 1993.

At the time, we had Physics, Chemistry, and Mathematics. Chemistry was a subject, yes, but I really didn't know much about it. I was only interested in Physics and to some extent, Mathematics.

**SS: So you didn't like Chemistry at all? Maybe even wished it wasn't there?**

**SM:** [Laughs] Yes, exactly. I knew very little, and I wasn't fond of it.

Anyway, I planned to spend the next year preparing for entrance exams. But in the meantime, I thought of taking admission to a nearby B.Sc. college. That's where I met two teachers who left a lasting impression on me - Kiranmoy Sen Sharma and Subir Ghosh. Their teaching was so inspiring.

**SS: May I ask where this college is?**

**SM:** Yes, it's quite close to my house - about one and a half kilometers away.

**SS: In Kolkata?**

**SM:** Yes, in Kolkata. So, what happened was - they started teaching mechanics and related topics, and I found it really quite interesting. Then, I think in the second year, they introduced quantum mechanics and so on. Actually, even in the first year itself, I became quite engaged with the subjects.

Gradually, I lost the motivation to appear for the engineering entrance exams again. I thought, "No, I'll drop that plan."

At that time, the University of Calcutta had this option - after completing a three-year B.Sc. degree, you could pursue a B.Tech in Radio Physics, Electronics, and similar fields. So, I started thinking, "Maybe I'll go for that instead."

**SS: Okay, so was it that you didn't want to appear for the entrance exams again, or was it more because you started enjoying the subjects in physics?**

**SM:** It was mainly because I started liking physics. I had initially thought of going into radio physics and related fields, but in the third year of B.Sc., we started learning topics like relativity and quantum mechanics - really fascinating subjects. Once I got into those, I felt it would be very difficult to leave physics behind.

I still considered going into radio physics, but my marks weren't that great. So, I thought - forget everything else, I'll go for an M.Sc. in physics instead.

So, I enrolled in the M.Sc. program. Around that time, I had a friend - I had a brief overlap with him in Class 11 - he was in the M.Sc. as well.

**SS: Where did you do your Class 11?**

**SM:** I did my Class 11 at St. Xavier's College, but I had known this friend from Jodhpur Boys' School. It's a long story [laughs]. Anyway, he was already at that college and also joined the M.Sc. program. He told me about this place called IUCAA - he suggested I attend a summer school there.

I thought, "Okay, he's quite knowledgeable, so I'll follow his advice." I applied and went to the summer school at IUCAA at the end of my first year of M.Sc. - and I found it to be a wonderful place!

That's when I decided: I should do my Ph.D. there. Of course, I had to clear all the competitive exams and go through the usual process.

**FIG** 1: Inter-University Centre for Astronomy & Astrophysics (IUCAA) at Pune. Prof. Mitra completed his PhD from IUCAA in 2006. He returned to the institute as a scientist in 2011, and has been carrying out his research there since then. [Source: pqmlab.iucaa.in]

**SS: So even back then, you had to appear for exams like NET and GATE?**

**SM:** I gave JEST, NET - these two exams. I also applied for TIFR and other places. But IUCAA was just too good, very comfortable.

**SS: So, you were a student at IUCAA, and now you are a faculty member there. Correct? Over these long years, how has IUCAA developed and evolved? Also, how is an institute like IUCAA different from universities such as Calcutta, Bombay, or institutes like IISER, IITs?**

**SM:** First, let me tell you something - IUCAA hasn't really changed much, and I have a theory about that. IUCAA was founded by Jayant Narlikar, who believed in the steady state theory, so maybe that's why! [laughs] But seriously, there have been changes, though I'd say they are relatively minor.

What has really changed is how science is done. Science itself is always evolving, but recently, collaborative science has become much more prominent. By collaborative, I mean scientists working on different parts of a project come together and pool their expertise.

For example, I was part of two major projects: the LIGO project and the Planck project. These kinds of large collaborations have always existed, but over the years, the number of people involved has grown significantly. Take LIGO - there are over 1,000 people in the collaboration! Think about how many astronomers there are worldwide; that shows the scale. And LIGO isn't the only one - there are other collaborations too, like in radio astronomy and Planck, which had a few hundred people.

This shift means that the era of a few "star" scientists leading everything is fading. Instead, we have groups working together, and the work is more distributed. Along with that, the number of astronomers in the country has probably increased, so that has also contributed to the change.

**SS: I had a conversation with Professor Nissim from NCRA. He mentioned that depending on who is the director or the main guiding person of an institute, the nature and functioning of that institute can change. But you're saying that over the years, science itself has evolved, while IUCAA has not changed that much?**

**SM:** Right, the administration of the institute - how it operates - does change. The amount of time you get for research can vary; sometimes you get more, sometimes less. But scientists are probably the most difficult people to convince to change. Getting them to do something other than what they want to do is almost impossible.

On the the other hand, directors have to optimise distribution of resources based on the goals of the institute and priorities of the researchers, which can impact research highly dependant on, say, experimental or computational facilities. But that maybe inevitable since the resources are limited.

**SS: So, you said funding can affect research, but it hasn't affected you much personally. However, when I talk to other professors or researchers at IISER or elsewhere, many say funding issues have affected them a lot over the years.**

**SM:** Yes, especially for experimental work, funding matters a great deal. If your experiment needs ten components and you get only nine, your experiment simply can't happen. You might make some progress, but you can't complete it. Funding is crucial.

Maybe I'm saying this because I was fortunate - LIGO India got funding, so that helped. Also, institute directors decide whether their institute will join these mega-projects, which changes the institute's dynamics somewhat.

For example, IUCAA is part of LIGO India. If I weren't involved in LIGO India, I'd probably spend more time on different gravitational wave research. But since IUCAA is part of LIGO India, I spend a lot of time working on the collaboration - even if it doesn't immediately lead to publications, it's important collaborative work.

**SS: Okay, so for our friends from other disciplines, what does LIGO stand for? What is LIGO, and what is LIGO India? Are they the same thing?**

**SM:** LIGO stands for Laser Interferometer Gravitational-Wave Observatory. It's a highly sensitive detector designed to detect

**FIG 2:** Prof. Mitra with Prof. Anand Sengupta of IIT Gandhinagar at IUCAA during his PhD. This picture was taken by Prof. Subharthi Ray, University of KwaZulu-Natal, Durban. [Source: web.iucaa.in/ sanjit/]

gravitational waves directly. Currently, it's the most sensitive instrument of its kind in the world.

There are two LIGO detectors in the US - one in Livingston, Louisiana, and the other in Hanford, Washington. These two detectors are placed far apart, almost diagonally across the country, to maximize the distance between them. While they can detect gravitational wave events, having only two detectors makes it difficult to accurately pinpoint the exact location of the source in the sky.

Localization - finding exactly where the gravitational wave is coming from - is very important because it allows other telescopes to follow up and observe the event in different wavelengths, like visible light or X-rays.

That's why we need a third LIGO detector, and that one will be in India - it will be called LIGO India. The detector will be built by the Government of India, while many crucial components will be supplied from the US. Originally, there were supposed to be three detectors in the US, with two co-located at Hanford, but that idea was dropped because co-located detectors tend to have correlated noise, which reduces their effectiveness.

LIGO India is a major project funded by the Indian government, through the Department of Atomic Energy and the Department of Science and Technology, with a Memorandum of Understanding (MoU) with the National Science Foundation (NSF), USA. The project budget is around 2600 crore rupees. The Indian detector will work as part of the global network of detectors along with the two LIGOs in the US, the Virgo detector in Italy, and potentially KAGRA in Japan.

### SS: Is KAGRA not operational right now?

**SM:** It is operational but at very low sensitivity, so its data is not very useful for astronomy at this stage. Both LIGO and Virgo detectors have 3-kilometer arms, while KAGRA is underground and also has 3-kilometer arms. Virgo's sensitivity is roughly one-fourth that of LIGO's, but it still contributes usefully. KAGRA's current sensitivity is only about 1% of LIGO's, so it's still developing.

### SS: Why do we need so many detectors?

**SM:** To localize gravitational wave sources on the sky, you need at least three detectors. With three or more detectors, you can triangulate the position of the source much more accurately.

Accurate localization is crucial because the electromagnetic telescopes that follow up these events usually have very small fields of view. If the localization region is large, by the time they scan the entire area, the signal might have faded.

In fact, the goal is to catch these events beforehand - early in the inspiral phase of the binary system. Here's how it works:

Two compact objects - like black holes or neutron stars - orbit each other and emit gravitational waves, which carry away energy. As they lose energy, they spiral closer together, and their orbital period decreases. This means the frequency of the gravitational waves goes up, causing them to emit waves even faster. It's an avalanche process leading to a final violent merger that we can detect.

### SS: So, the more the two objects come together, they emit gravitational waves at an even faster rate? The more they emit, the periodicity goes up?

**SM:** Yes, exactly. The frequency goes up as they spiral closer, and they emit gravitational waves more rapidly. It's like a nonlinear collapse process. Even before the two objects actually merge or touch, if the detectors are sensitive enough, we can detect them

**FIG** 3: Global Network of Gravitational Wave Detectors: Clockwise from top left - LIGO Hanford (USA), KAGRA (Japan), LIGO Livingston (USA), and Virgo (Italy). Together, these state-of-the-art observatories listen to the ripples in spacetime caused by cataclysmic cosmic events. LIGO-India (Laser Interferometer Gravitational-Wave Observatory) is a planned advanced gravitational-wave observatory to be located in India as part of the worldwide network. **Sanjit Mitra** is a LIGO-India Project Coordinator. [Source: ligo.caltech.edu] early and predict that something is going to happen within seconds or maybe a few minutes - at least about a minute before.

If we can detect the signal a minute beforehand, then electromagnetic telescopes can point to the right spot in the sky in time to catch the event.

For example, in a black hole–neutron star merger, the neutron star can get tidally disrupted by the black hole just before merging. If we have early warning, telescopes can capture this tidal disruption event.

There was an event called GW170817 in August 2017. After the merger, telescopes pointed there and observed it for months. We know what happens after the merger, but tidal effects before merging - which could tell us a lot about neutron stars - haven't been observed clearly yet.

### SS: So, in layman's terms or in a bit of a fantasy way, the gravitational waves are like a prequel or a trailer, and the telescopes see the sequel - the electromagnetic signals after the event?

**SM:** Yes, that's a good way to put it. LIGO India coming online will help us localize the source well enough to tell telescopes where to look.

If the sky localization isn't accurate, telescopes don't know where to point, so good localization is crucial.

### SS: Why do we need three detectors exactly?

**SM:** It's like GPS satellites. With two detectors, you can only narrow the source down to a ring or a band in the sky. To pinpoint the exact location, you need at least three detectors - three intersecting circles give you a precise spot.

### SS: So with LIGO, plus LIGO India, we'll have three detectors, and their combined data will allow us to pinpoint the source?

**SM:** Each pair of detectors gives you one constraint - essentially a circle (or more accurately, a ring) on the sky where the source could be. This is based on the time delay between when the signal reaches each detector.

For example, if the time delay between two detectors is zero, the source must lie in the plane that bisects the line joining the two detectors.

If one detector receives the signal a millisecond earlier, then the source must be in a location that creates a path difference corresponding to that millisecond. This helps narrow down the source direction.

When you combine this timing information from multiple pairs of detectors, a method called triangulation, you can localize the source much more precisely.

### SS: So LIGO is already doing this. Then what's the role of VIRGO and KAGRA?

**SM:** Good question. The key point is: for triangulation to work well, you need at least three detectors taking good data at the same time.

However, gravitational wave detectors like LIGO, VIRGO, or KAGRA are not always collecting usable data. Even when operational, they give useful data only about 70–80% of the time. Let's take 70% for calculation.

So, the probability that three specific detectors (say, Livingston, Hanford, and VIRGO) are all operating and giving usable data at the same time is:

$0.7 \times 0.7 \times 0.7 = 0.343$ or 34.3%

### SS: So, each detector has about a 70% uptime, and for three together, it's about 0.7 cubed?

**SM:** Yes, exactly. But if we now ask: what's the probability that at least three detectors are collecting data when you have four detectors available, the math becomes a bit more involved. But that probability turns out to be about 65% - almost double.

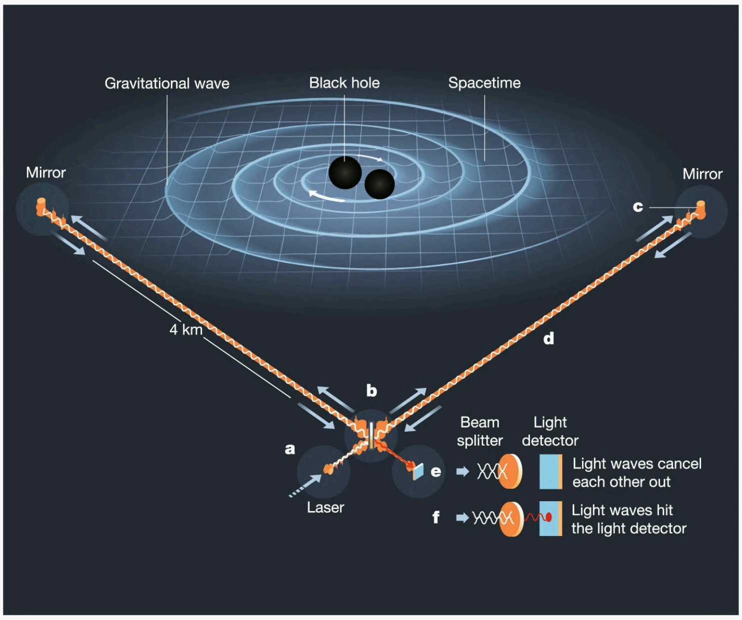



**FIG 4:** This diagram shows how scientists detect gravitational waves-tiny ripples in the fabric of spacetime - using a tool called a laser interferometer, like LIGO or Virgo. A powerful laser (a) sends a beam of light to a beam splitter (b), which divides it into two identical beams that travel down two long arms - each 4 kilometers in length (paths b→c and b→d). These beams reflect off mirrors (c and d) and return to the beam splitter, where they recombine. Under normal conditions, the two light waves are perfectly synchronized and cancel each other out (e), meaning no light reaches the detector. But if a gravitational wave - like one from two black holes merging - passes through (top of image), it subtly stretches one arm and squeezes the other (d). This tiny shift (smaller than a proton!) disrupts the perfect balance of the light waves. Now, they no longer cancel completely and some light reaches the detector (f), signaling that a gravitational wave has passed. [Illustration: ©Johan Jarnestad/The Royal Swedish Academy of Sciences]

So, with more detectors, not only does your uptime for triangulation go up, your sky localization improves drastically too.

Currently, we have three main baselines: LIGO Livingston, LIGO Hanford and LIGO Louisiana. When LIGO India comes online, it will form new baselines: LIGO India - Livingston, LIGO India - Hanford and LIGO India - Louisiana. So, the total number of independent baselines increases from 3 to 6. Of course, change the name of the places (laughs!)

Moreover, the average length of these new baselines (especially with LIGO India, which is geographically farther apart) is about 1.5 times longer than the existing ones. Longer baselines give better angular resolution, meaning more precise localization of the source on the sky.

So, LIGO India won't just be an extra detector - it will significantly boost both the accuracy and reliability of global gravitational wave detection.

**SM:** More detectors not only improve sky localization, but also increase the signal-to-noise ratio (SNR). That's why adding more detectors is essential.

Now, there's another interesting point:

VIRGO and KAGRA use different technologies, developed independently. KAGRA, in particular, is quite different. However, they haven't yet matched LIGO's sensitivity, and may not reach that level soon.

LIGO-India, on the other hand, will use the same technology as LIGO (US). So, it's expected to achieve comparable sensitivity. And since the site in Maharashtra is one of the best in the world, LIGO-India could become the most sensitive detector globally. That's very exciting.

### SS: How do you decide what makes a site "best"? These events are far away in space. Does location - like Moscow or Sri Lanka - really matter?

**SM:** Astrophysically, it doesn't matter where you are. But for the detector's functioning, it absolutely does.

Gravitational waves are detected by measuring changes in the distance between two mirrors 4 km apart, using laser interferometry - down to one-thousandth the size of a proton.

That's incredibly precise, so seismic noise and local disturbances must be minimal. While multi-stage suspension systems reduce this noise, if the site itself has high inherent noise, it limits sensitivity. That's why site selection is critical.

### SS: Inherent noise means?

**SM:** It refers to ground noise - mainly anthropogenic (like traffic) and non-stationary (varying over time). If this noise is high or fluctuates too much, it becomes hard to operate the detector.

### SS: So it's like putting a paper on a table - if the table shakes, the paper shakes too.

**SM:** Exactly. Or think of mirrors hanging like a pendulum. If you move your hand holding the rope, the stone swings. Similarly, if the detector base shakes, the mirrors move. That's why detectors must be far from cities - daytime noise from cars is higher than nighttime. These things affect sensitivity.

### SS: So we need a location that's calm - anthropogenically, geographically, and geologically.

**SM:** Right. Geologically, you want low ambient seismic noise - not near the sea, because even sea waves create ground vibrations.

### SS: So not in the Himalayas either - they're geologically active.

**SM:** Yes, the Himalayas are too seismically active. While occasional earthquakes are manageable (the detector can be reset), in regions with frequent or strong earthquakes, there's a real risk of permanent damage. So those sites are avoided.

### SS: So, the Himalayas aren't really an option?

**SM:** Yes, placing the detector there would be very difficult and risky due to the high seismic activity.

### SS: And since major rivers originate there, the entire Ganga–Brahmaputra basin should also be avoided?

**SM:** Exactly. That region has been avoided. Instead, we focused on the Deccan Plateau, which is geologically more stable. Several sites were surveyed there, as well as in places like Rajasthan.

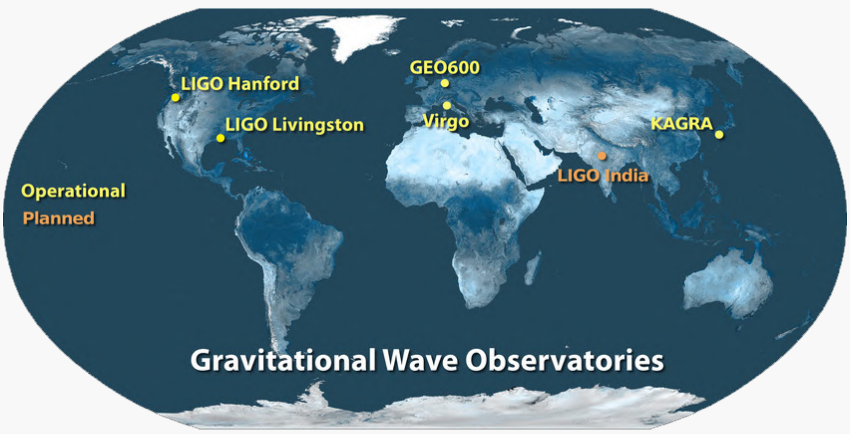



**FIG 5:** Position of gravitational wave detectors world wide (current and future). Having more gravitational-wave observatories around the globe helps scientists pin down the locations and sources of gravitational waves coming from space. [Source: ligo.caltech.edu]

**SS: So it's not just astrophysicists working on this project.**

**SM:** Exactly. Site selection isn't based only on astrophysical considerations. For the science part, it doesn't really matter where in India the detector is, but it has to be quiet, geologically stable, far from airports and highways, but not too remote - since scientists and engineers need to travel and work there regularly.

**SS: Nissim sir also mentioned that some detectors are placed in deserts, which is good for isolation, but maintaining them becomes expensive and difficult.**

**SM:** Right. Science needs people, and humans have to operate and maintain these detectors. That's a practical constraint - we can't go too remote.

**SS: But what if the area around Hingoli becomes populated in 20–25 years? Cities might develop.**

**SM:** That's a real concern. It happened with observatories like IUCAA's Girawali, where the sky used to be dark, but after 20 years, there's now significant light pollution. GMRT also faced issues from mobile towers. For LIGO-India, we've taken some protective measures - there are agreements in place to prevent heavy industrial activity nearby, at least for the near future. We'll try our best to preserve the environment around the site as long as possible.

**SS: How do detectors work?**

**SM:** The LIGO detectors are essentially very sophisticated Michelson interferometers. Each has two perpendicular arms with mirrors at the ends and a beam splitter at the intersection. A laser beam is split into the two arms, reflects off the mirrors, and recombines to detect interference caused by passing gravitational waves.

Now, in basic labs, you may have worked with small Michelson interferometers. For LIGO, we need to detect gravitational waves with wavelengths on the order of 1,000 km, but obviously, we can't build arms that long. The actual arms are 4 km each, but we increase the effective path length using Fabry-Pérot cavities - by placing additional mirrors near the beam splitter, the laser light bounces back and forth roughly 300 times. This increases the effective arm length to about 1,000 km.

However, even with so many bounces, leading to orders of magnitude increase in laser power, shot noise becomes a major issue. It's like trying to take a clear photo in the dark - you need more light. To combat this, LIGO uses a continuous-wave laser, currently at 70 watts, scalable up to 125 watts. This is among the most powerful continuous-wave lasers ever built. Note that while higher-powered pulsed lasers exist, continuous-wave lasers of this strength are rare and essential for LIGO's precision.

**SS: How can students like me - or future students - contribute to the LIGO project? And how can we benefit academically from being involved in such a large-scale experiment?**

**SM:** LIGO-India is a mega-science project, and it's inherently multidisciplinary. Almost every topic in a physics curriculum connects to LIGO in some way - gravitational waves tie into classical mechanics, quantum optics, relativity, statistical physics, and even thermodynamics. You'd be hard-pressed to find a concept in physics that isn't somehow relevant.

The same goes for engineering: mechanical, electronics, computer science - all are deeply involved. For instance, the thin-film coating on the LIGO mirrors remains an active area of research. Even chemistry plays a role - in cleaning and maintaining the optics, understanding materials, or mirror surface interactions. And while biology might seem unrelated, there was a case (though anecdotal) where bacterial corrosion was suspected in vacuum tubes, requiring biological expertise to mitigate the issue.

So yes, while some disciplines are more involved than others - like physics, engineering, and mathematics - others like chemistry, and occasionally biology, also find surprising relevance.

**SS: So, to summarize: physicists, engineers, chemists, maybe even biologists - all can find a place to contribute to LIGO.**

**SM:** Exactly. It's a collaborative ecosystem, with varying levels of involvement depending on the field. But if you're curious and open to interdisciplinary learning, there's a role for you.


**FIG** 6: Prof. Sanjit Mitra responding to questions of the then Union Minister of State (I/C) Ministry of Development of North Eastern Region, MoS PMO, Personnel, Public Grievances and Pensions, Atomic Energy and Space, Dr. Jitendra Singh who visited the LIGO-India booth at the inauguration function of the Vigyan Samagam mega science exhibition in February 2020. [Source: LIGO India Facebook page]

**SS: To shift gears a bit - how do you feel the Indian education system has changed over the years?**

**SM:** Frankly, I expected much more progress in our education system. Over the last 20 years, I thought we'd be significantly ahead, but I don't see major improvements. In fact, in some ways, we may have even regressed.

**SS: Regressed? As in fallen behind?**

**SM:** Possibly. It's difficult to measure education precisely, but any nation that invests thoughtfully in education and science sees long-term returns. The real aim of education should be to teach students how to think, not just how to solve standard problems or memorize facts.

**SS: So you feel we've not made progress in nurturing that kind of independent thinking?**

**SM:** Exactly. What I see instead is students overwhelmed by constant assignments and evaluations, leaving little time for genuine thinking or exploration. Yes, continuous assessment keeps students engaged, but what does "progress" really mean? Just solving problems set by a teacher?

**SS: Assignments, exams - that's how we define success today.**

**SM:** And that's precisely the problem. Real progress is when students feel intrinsically motivated to learn, explore beyond the syllabus, and think independently. That's how researchers are shaped - not by simply following instructions.

**SS: So where do you think we've gone wrong?**

**SM:** One issue is the shift from older systems. When I was a student, we had annual exams. We had the whole year to learn in our own way, and only one exam at the end. Sure, some students didn't study and struggled, but even forcing them to study all year wouldn't have made much difference if the drive wasn't there.

**SS: But isn't that risky - like a one-day match? What if someone just has a bad day?**

**SM:** True, but the deeper question is - why are we evaluating, and what are we evaluating? Evaluation should help growth, not dominate the learning process.

Today's system robs students of time for creative exploration. When I was a student, I could spend time reading from different books, trying things my way. That's missing now.

**SS: So the older system actually helped you grow?**

**SM:** Yes, definitely. It wasn't perfect - it had loopholes. But instead of improving it, we've completely replaced it. Now, students follow instructions from multiple teachers across subjects. But how do we know all of them are teaching in the best way? Even I wouldn't claim my method is perfect. If we rely solely on teachers' methods and instructions, we're placing enormous trust in individuals. Without space for alternative approaches or exploration, we limit the very essence of education.

**SS: So can't we just establish certain standard books - those that are locally or globally accepted? For optics, many trust Ajay Ghatak's book.**

**SM:** Sure, but if everyone blindly trusted one book, there would never be new ones. Even Ghatak must have learned from older texts. If he had just trusted those, we wouldn't have his book today. That's the issue - we often say "this is the book to follow" simply because it's convenient. But true learning comes from comparing, questioning, and exploring beyond just one source. There may be a better book which you would be able to write and this is how things will progress because we are showing extreme faith in everything we have right now.

**SS: If you had the power to reform the Indian education system, what changes would you make?**

**SM:** Reforming the entire system isn't something one person can do. But in my small way, I try to provoke students to think rather than overload them with assignments. I don't believe in constant performance monitoring through regular assessments. Maybe two or three exams in a year are enough. If a student isn't interested, it's better they disengage early - academics should be for those who truly enjoy learning. Forcing uninterested students benefits no one.

See, we need to trust students. They're adults - over 18. If they're genuinely curious, they'll come to class not to be spoon-

**FIG** 7: Left to Right: Tarun Souradeep (LIGO-India Project Coordinator, IUCAA); Umakant Rapol (IISER, Pune); Rana Adhikari (LIGO Scientific Collaboration, Caltech), and Sanjit Mitra (LIGO-India, IUCAA) having relaxed dinner-time discussions about LIGO-India experimental program at Centre for Gravitational Physics and Astronomy, Pune. [Source: LIGO-India] fed, but to learn how to approach problems. A good student learns how to learn.

A good teacher creates independent learners. The best students are those who can learn on their own. The goal is not to create followers, but empowered thinkers. Ask yourself: what's more valuable - a good teacher or a good student? It's the student. A good teacher's success is in creating good students.

**SS: So, tell me, what is more important ? A good teacher or a good student ? Getting analogy from the Mahabharata, who is more important - Dronacharya or Arjun?**

**SM:** It's about resonance. Arjun had potential, but a different teacher might not have brought it out. Good students don't appear on their own. Good teachers help shape them - but the goal is still to make the student shine, not just obey.

**SS: In that context, what do you think of the National Education Policy (NEP)?**

**SM:** I haven't studied it deeply, but some of the ideas - like flexibility in subject choices and the credit bank - are good in theory. However, if not implemented properly, it can be problematic. For instance, many colleges already struggle with the 3-year BSc structure. Extending it to 4 years without proper infrastructure could make things worse. People might assume a 4-year degree is inherently better, but in reality, the quality could deteriorate.

**SS: Why do you think students today tend to lean more toward technical fields rather than pure science?**

**SM:** I don't think that's new. Even when I chose science, people questioned why I wasn't going into engineering. Pursuing science requires a certain level of economic security. If someone is worried about basic needs, they'll naturally prioritize jobs and income. That said, our research institutes still attract many strong PhD students. I just wish there were more.

**SS: Do you believe in the "brain drain" theory?**

**SM:** Not really. If someone wants to go abroad, let them. Sometimes, it makes sense to go where the best research is happening. But I often feel people go with the assumption that foreign research is automatically better. If they stay back, they may feel they're missing out - and that lack of commitment can impact their work. You achieve the best results when you're fully invested in what you're doing.

**SS: Suppose your current resources were reduced due to policy changes or external factors. Would you still be able to achieve your research goals?**

**SM:** It would certainly affect the outcomes. Reduced resources mean reduced capacity. Some impact is inevitable.

**SS: But when another country calls you, and you're offered an opportunity - maybe not significantly better, but comparable - you tend to go. Let's not talk about big names like the US, UK, or Russia. Even a smaller country can sometimes provide the support you need. Especially if you're working on experiments or need high computing power, and those resources aren't available here - then yes, it makes sense to go. And that's where the idea of brain drain becomes relevant. You wanted to stay, you contributed here, like to LIGO-India, but when resources start drying up, naturally you start looking elsewhere. Say you're contributing to LIGO-India, and a month from now, your resources are slowly getting cut off - yet you still get some support. But suppose another country - say, the Philippines - offers you better support. Even if it's not a "lucrative" destination by general standards, you might consider moving.**

**SM:** To be honest, it's hard for me to answer this objectively. I'm part of LIGO-India, and that's been a fantastic move by the government. Had India missed this opportunity and the third detector gone to another country, it would've been a disaster for us. People like me might still have chosen to stay in India, because I'm comfortable here and I like it. But I would've been disappointed. Some people love science more than the country, convenience, or community. That's not a bad thing - science progresses because of people like that. They go where the science takes them, and maybe that's how it should be. If I'm not doing that, maybe I'm the one in the wrong.

For example, if you're doing gravitational wave research in India - especially theory, data analysis, or detector characterization - I don't think you'll find a significantly better environment anywhere else. Sure, there are experts across the world, but in India, we have a unique structure.

**FIG 8:** Prof. Mitra with Dr. Atul Deep, who works at ESA, during his PhD days at IUCAA. [Source: web.iucaa.in/~sanjit/]

**FIG** 9: Prof. Mitra at The Future of Gravitational-Wave Astronomy, a discussion meeting at International Centre for Theoretical Sciences [Source: LIGO India facebook page]

The LIGO-India Scientific Collaboration (LISC) is one of the largest in the world right now. We meet weekly online. Any problem you have - someone will solve it. The group has more than 100 people, with very diverse backgrounds. You'd be hard-pressed to find such a diverse, supportive, and active group elsewhere. And we have full academic freedom. There's no pressure to work on a fixed problem. Funding is secured for five years. Where else do you get that kind of flexibility?

Of course, government policies - whether from the present or previous administrations - do affect scholarships and funding. These cuts have real consequences. Every year, we see basic statistics showing our research output is declining. It's not that every country is doing better, but we certainly shouldn't be slipping. China, for example, is pouring enormous funds into research - there's no comparison. They'll do very well. But in gravitational waves, India still has enormous expertise. This is a great place to be - at least for now. Funding cuts will definitely impact instrumentation. Fortunately, LIGO- India is already funded, so we're not seeing that impact directly yet. But if future instruments aren't funded properly, it will hurt.

### SS: Do you regret not following the other path?

**SM:** No. What scares me is what would have happened if I had succeeded in those earlier exams. I would've likely taken a completely different route. Maybe that would've been the wrong one.

### SS: Or maybe not. Maybe you'd have loved that path too?

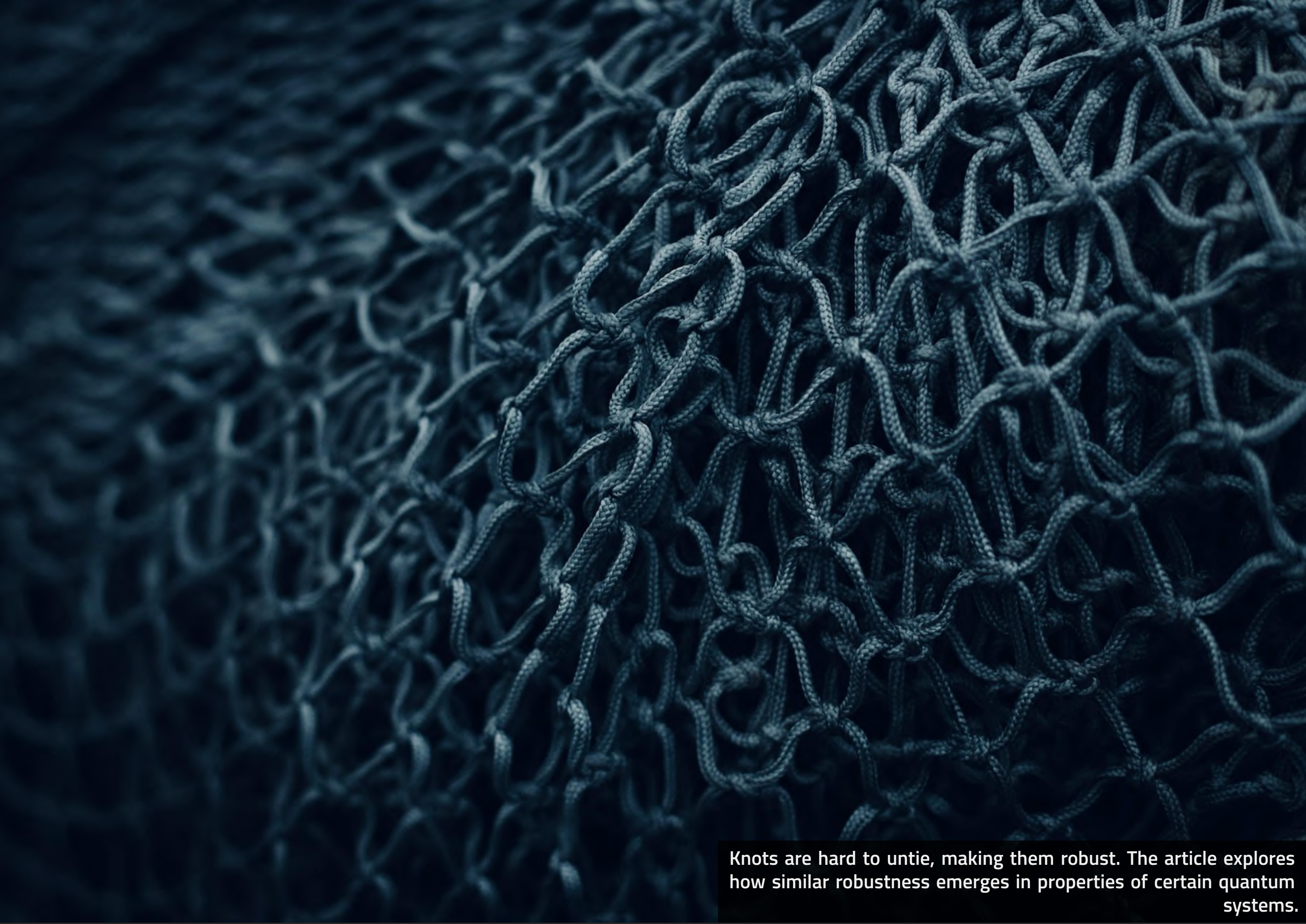
**SM:** Maybe. It could be that my personality is such that I'd have liked whatever I ended up doing. But I still feel I'm in an optimally placed position now. Whatever happened, happened for the best. Then again, if something else had happened, maybe I'd be saying the same thing about that path too. We'll never know.

### SS: Finally, any advice to my friends?

**SM:** You know, like you asked earlier about how I came into gravitational waves - it was never a straight path. I was determined to do something, and then something else came along that I

liked more, and I took that instead. I thought, "Oh, this seems better." And this is my advice. Just do what you like.

### SS: Thank you, sir.



Knots are hard to untie, making them robust. The article explores how similar robustness emerges in properties of certain quantum systems.

# Topology in Action: From Doughnuts to Quantum Devices


## Sukalyan Deb (Department of Physical Sciences, IISER Kolkata)



Topology focuses on the global properties of systems, ignoring precise details like size or angles. This article explores its origins in Euler's *Seven Bridges of Königsberg* problem, and trace its profound impact in condensed matter physics from the quantum Hall effect to topological insulators and quantum computation.



*Also available online, at scicomm.iiserkol.ac.in*



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**CATEGORY**
Physics

**Sukalyan Deb** is a PhD scholar in the Department of Physical Sciences in IISER Kolkata, currently working in theoretical physics, focusing on strongly correlated systems.

Mathematics has long served as the language of physics, helping us express and understand the laws of nature. From Newton's second law, which led to the development of calculus, to Schrödinger's equation in quantum mechanics, math enables us to model how the universe behaves. More abstract tools like group theory allow us to classify phases of matter by their symmetries - or more interestingly, by how those symmetries are broken.

But there's another powerful branch of mathematics that's become essential in modern physics, especially in studies of condensed matter systems: **topology**.

Topology studies the properties of spaces preserved under **continuous deformations** - stretching, bending, or twisting - without tearing or gluing. Imagine a rubber sheet: you can stretch or compress it into various forms, but as long as you don't puncture it or attach new parts, the sheet remains topologically the same. These types of deformations, where the object is smoothly transformed without cutting or gluing, are called continuous deformations.

This is the key difference between topology and geometry. Geometry is concerned with precise measurements: angles, lengths, and areas. Two geometric shapes are considered different if those measurements differ. In contrast, topology focuses on the more abstract, structural aspects of a shape - **how it's connected**, how many holes it has, whether it's bounded or unbounded. In a topological sense, a coffee mug and a doughnut (torus) are the same because **each has one hole**; their detailed shapes and sizes are irrelevant (Fig 1).

## How to quantify topology: Topological invariants

One of the oldest and simplest tools in topology is the **Euler characteristic**, a number associated with a geometric object. For a polyhedron, it's defined as

$$\chi = V - E + F$$

where V is the number of vertices, E the number of edges, and F the number of faces. Take a tetrahedron: it has 4 vertices, 6 edges, and 4 faces. Plugging these into the formula gives

$$\chi = 4 - 6 + 4 = 2$$

. A cube has 8 vertices, 12 edges, and 6 faces, giving

$$\chi = 8 - 12 + 6 = 2$$

again. In fact, for any convex polyhedron, this number is always 2. This is no coincidence - these shapes all share the same underlying topology: **they are topologically equivalent to a sphere**.

What makes the Euler characteristic especially important is that it is a **topological invariant** - a quantity that remains unchanged under continuous deformations. So if you smoothly stretch or bend a cube into a sphere, its Euler characteristic stays the same. But if you punch a hole through the object, turning it into something like a torus (a doughnut shape), the Euler characteristic changes. For a torus, $\chi = 0$. That difference tells us the two shapes are topologically distinct- they belong to different "families" of spaces (Fig 2).

Topological invariants like the Euler characteristic allow mathematicians and physicists to **classify shapes and spaces** in a way that's robust against local


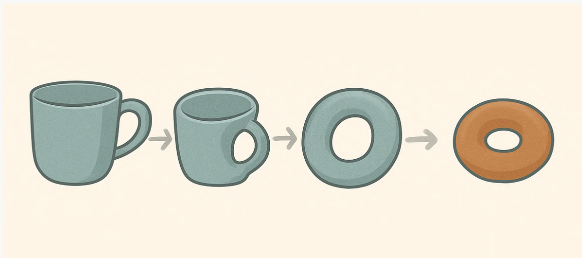

FIG 1: *Left*: A cup (with a handle) is topologically the same as a doughnut but topologically inequivalent to a bowl. This is because while a coffee cup and a doughnut both have the same number of holes (1), a bowl has no holes. *Right*: Shows pictorially why the cup is equivalent to a doughnut. Starting from the cup, one can gradually make continuous deformations (changes that do not introduce or remove holes into the system) and eventually form a doughnut. Because one can be transformed into the other through continuous deformations, we say that the objects are topologically equivalent.

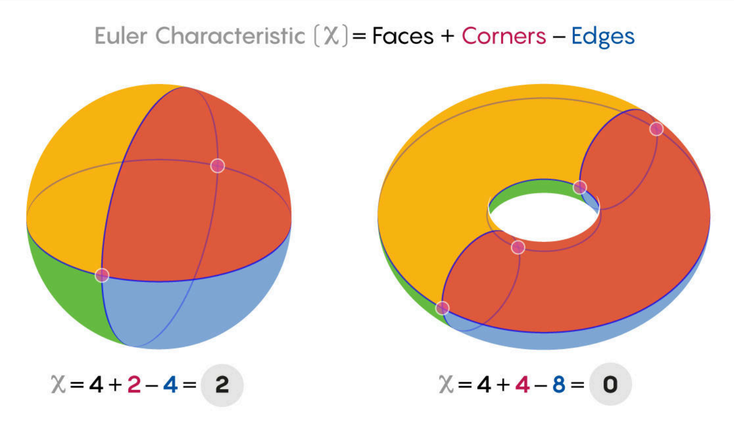


**FIG** 2: The Euler characteristic is an example of a topological invariant that distinguishes between objects with different topologies (sphere and torus in the figure). The sphere (left) can be divided into four regions (differently coloured). This creates four faces F (red, orange, green and yellow), four edges E (blue lines that separate at least two distinct faces) and two vertices/corners V (where at least two edges meet). The Euler characteristic then works out to be $\chi = F - E + V = 2$. In the same way, the torus divides into four regions but the presence of the internal hole means there are 8 edges and 4 verticles, leading to $\chi = 4 - 8 + 4 = 0$. [Credit: Quanta Magazine 2020]

disturbances. Rather than tracking every detail, we focus on what truly matters: how the space is connected, how many holes or boundaries it has, and how it behaves as a whole.

## The Problem of the Seven Bridges of Königsberg

Looking back through history, we find that topology originated from a mathematical problem posed by Euler in 1736 [1]. This problem, known as the **Seven Bridges of Königsberg**, holds historical significance. The problem is rooted in the unique geographical layout of the 18th-century city of Königsberg, then part of Prussia (now Kaliningrad, Russia). Situated along the Pregel River (now known as the Pregolya), the city encompassed two large islands-Kneiphof and Lomse-formed by the river's branching channels. These islands were connected to each other and to the mainland by a total of seven bridges, creating a complex network of crossings (shown in Fig. 3) . This configuration led to a natural curiosity among the city's inhabitants: **is it possible to devise a walk through the city that crosses each bridge exactly once without retracing any steps?**.

At first glance, this seems like a challenge of planning or persistence. One might start at one part of the city-say, on one of the islands-and attempt a path that carefully crosses each bridge without retracing any steps. Maybe try crossing to the northern bank, then loop through the western side, come back to the island, and finish on the southern bank. **But no matter how carefully you plan, you'll find yourself stuck: either forced to cross a bridge you've already used, or stranded with no remaining bridge to exit from.**

People naturally attempted many such trial-and-error strategies. Some tried drawing the path, others tried tracing routes on a map. Yet none succeeded.

## Euler's solution and the birth of topology

In order to tackle the problem, Euler performed an **abstraction** on it - he removed all irrelevant features and information (such as the lengths of bridges and sizes of landmasses) and retained only the necessary components. He realised that each land mass can be simplified by representing it as a node (gray points in Fig. 4), and the seven bridges can be viewed as connecting edges between these nodes (orange lines in Fig. 4). In modern mathematics, this is called a **graph**.

Note that the initial problem that was posed was to figure out if it's possible to traverse all bridges exactly once, without retracing steps. **Euler noted that this problem is equivalent to figuring out whether one can construct a path along the graph that traverses every edge exactly once while passing through every node**. In order to do this, certain constraints must be obeyed by the path. The starting and ending nodes (which correspond to the landmasses you start

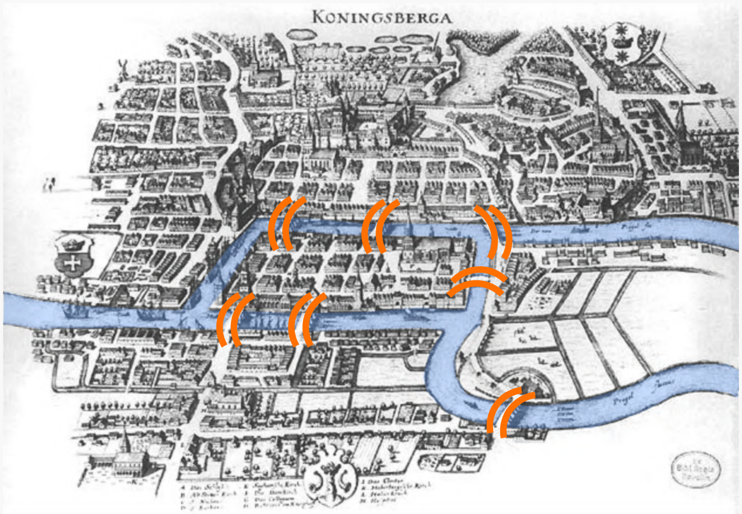


**FIG** 3: A stylized historical map of Königsberg, where seven bridges (orange marks) connected four different parts of the city separated by the river Pregel (blue). This setup posed a famous problem: is it possible to walk through the city crossing each bridge exactly once? Euler's resolution of this question in 1736 marked the birth of graph theory and laid the foundations for modern topology.

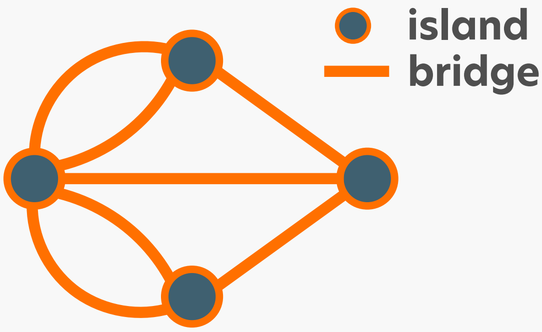


**FIG** 4: Abstracted graphical form of the Seven bridges problem. The blue circles represent landmasses while the connecting orange lines represent bridges. Euler noted that the original problem was equivalent to figuring out whether one can construct a path along the graph that traverses every edge exactly once while passing through every node.

from and end at) must have at least one edge attached to them (you must have a bridge to move out of the starting landmass and a bridge to move into the final landmass). The other nodes must have an even number of edges connected to them, because if you enter a landmass using a bridge, you must exit it using a different bridge (retracing steps is not allowed).

In mathematical terms, if a non-terminal node is traversed $n$ times, it must therefore be attached to $2n$ number of distinct edges (if you pass through a landmass 2 times, you must have 4 distinct bridges connecting it, otherwise you will retrace your steps at some point). Since only two nodes can be the terminal nodes, we have the constraint that at most two nodes in our graph can have an odd number of nodes; all other nodes must have an even number of nodes. **This means that in order for a solution to exist, at most two of the landmasses can have an odd number of bridges attached to it, the rest of the regions must have an even number of bridges.** In the specific graph problem we are encountering (Fig 4), we see that all the nodes in fact have an odd number of edges attached, thereby showing that no path with the specified requirements can be constructed for the Königsberg problem.

Note that the solution of the problem **required no knowledge of the shape and size** of the landmasses or the lengths of the bridges; the only relevant details were the **connections among the nodes**. In fact, distorting the size and shapes of the nodes or displacing the nodes by small distances does not alter the solution in any way. The solution is therefore **impervious to continuous deformations**, and is dictated purely by the topology of the graph. In this way, the Königsberg bridge problem also led to the birth of topology as a new field of mathematics.

## Topology in action: The quantum hall effect

Topology is not just a fancy mathematical construct-it plays a profound role in modern physics, particularly in understanding exotic phases of matter. A classic example is the **quantum Hall effect**. This is a juiced-up version of the classical Hall effect [2] in which a perpendicular magnetic field applied on a current deflects the electrons perpendicular to the current in the plane perpendicular to the field, and makes them accumulate on the boundaries, due to which an electric voltage (Hall voltage, $V_H$) develops in the same direction. The Hall resistance $R_H$, defined as the ratio of Hall voltage to longitudinal current ($I$),

$$R_H = \frac{V_H}{I} \quad ,$$

increases linearly with magnetic field in the classical case:

$$R_H(\text{classical}) \propto B \quad .$$

However, in a two-dimensional system with a bit of disorder (e.g., impurities or imperfections in the material) - such as a thin film of semiconductor subjected to very high **magnetic fields** and very low temperatures, the Hall resistance no longer follows a smooth linear trend. Instead, it exhibits a series of **quantized, precise plateaus** - meaning the Hall resistance takes on discrete values, each corresponding to a specific fraction involving fundamental constants (Fig 5):

$$R_H(\text{quantum}) \propto \frac{1}{n}\frac{h}{e^2}, n = 1, 2, ...$$

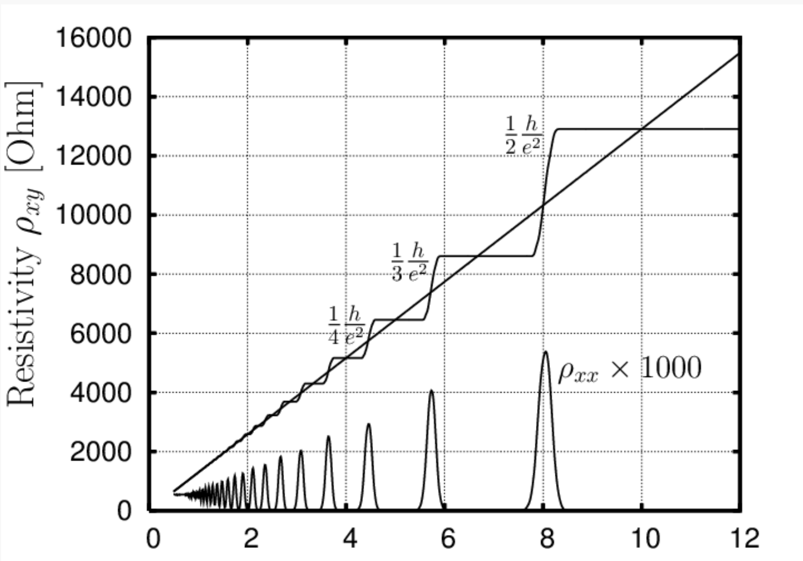


**FIG** 5: Comparison of Hall resistance behavior in different regimes. In classical systems (solid straight line), the Hall resistivity increases linearly with the magnetic field. In contrast, under strong magnetic fields and low temperatures, the system enters the quantum Hall regime, where the Hall resistivity forms sharply defined plateaus at quantized values. These plateaus are robust against disorder and signal topological protection.

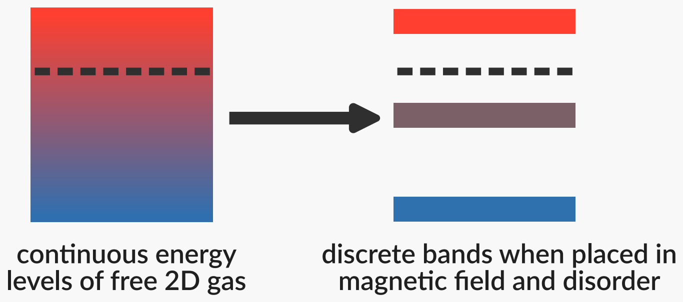


**FIG** 6: Evolution of electronic energy levels under the influence of a magnetic field. In the absence of a magnetic field (left), energy levels of a free-electron gas are continuous. Under strong magnetic fields and disorder (right), the energy levels split into discrete Landau levels, with each level broadened into a band by impurities. The emergence of localized and extended states within these broadened bands is key to the quantized behavior of the quantum Hall effect.

where $h$ and $e$ are the Plancks constant and charge of electron. This is the quantum hall effect [3]. Its most remarkable feature is the **robustness of these plateaus**: they are unaffected by imperfections in the material, such as impurities or small variations in geometry. This stability is a hallmark of topological phases of matter [4].

A peculiar property of magnetic fields is that they have a strong directionality - they **localise electrons** in one direction and force them to move in another direction. This localisation has a severe effect on the energy levels of the 2D electrons. In the absence of magnetic fields and any impurities (disorder), the energy levels vary smoothly (left, Fig 6);

$$E(B=0) \propto p^2 \quad ;$$

adding impurities and turning on a perpendicular magnetic field makes these levels bunch up into **discrete bands called Landau levels** (Fig 6):

$$E(B \neq 0) \propto n + \frac{1}{2} \quad , n = 1, 2...$$

Each value of $n$ represents a distinct Landau level. Each Landau level is macroscopically **degenerate**, consisting of a huge number of electronic states at the same energy. These degenerate states in each Landau level are spatially distributed along the transverse (Hall) direction, each state **localised** (cannot travel too far) at various positions [5], but are **extended** (can travel from one end to the other end) in the longitudinal direction.

## Origin of quantisation: Chiral edge states

It's important to note that **disorder** plays a crucial role in enabling the quantized Hall plateaus. By localizing most bulk states in between Landau levels, disorder prevents small changes in electron density from altering the number of conducting channels. This makes the quantization **experimentally robust**.

We will now figure out how topological considerations play into the robustness of the quantum hall resistivity plateaus, using a semiclassical picture. As mentioned in the previous section, each Landau level has multiple states with the same energy but placed at various positions along the localised direction. Away from the edges of the sample, the electrons in these states **circulate in closed cyclotron orbits** due to the magnetic field and do not contribute to any conduction mechanism. What happens when we consider states that are very close to the boundary, at a distance less than the radius of the cyclotron orbits? This is shown in the blue and red trajectories of Fig 7 - under the influence of the magnetic field, electrons try to exit the sample but of course cannot, and they reflect off the edge, **forming skipping orbits**. These states therefore extend along the length of the sample, and are **not localised** [6].

The important point is that the directionality of the magnetic field forces these delocalised skipping orbits to move in a certain direction - rightwards on the top edge and leftwards on the bottom edge, as shown in Fig 7. **There cannot be any left(right)-moving states on the upper(lower) edge**. Such states that move only left or right are called **chiral states**, and are generated because of the strong magnetic field [3]. More precisely, such chiral edge states result from the **time-reversal symmetry-breaking** nature of the magnetic field. A video of a time-reversal symmetric system looks the same if the video is played backwards. The magnetic field makes this impossible, because it separates the left and right-going states and places them on different edges - playing the video backwards would lead to a switch in the behaviour of the two edges. This separation also makes them robust - an electron travelling along an edge (as mentioned in the previous paragraph, the edge states are delocalised and can therefore carry current) **cannot stray from its path without expending a large energy cost**. To do so, it must "jump" to the other edge state (which is of similar energy), but since these states are **widely separated in real space** (they lie on opposite edges), such processes are effectively impossible.

How does the presence of chiral edge states explain the quantisation of resistivity in the plateaus? Given that each Landau level contributes one pair of **robust delocalised current-carrying** edge states moving in opposite directions

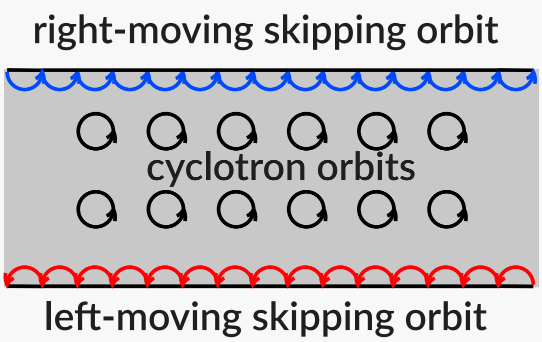


**FIG** 7: Depiction of chiral edge states in a two-dimensional electron system under a strong perpendicular magnetic field. In the bulk, electrons follow closed cyclotron orbits and remain localized. Near the boundary, these orbits are interrupted, creating skipping trajectories that propagate in one direction along the edge. These unidirectional states are topologically protected and form the basis of dissipationless edge transport in the quantum Hall effect.

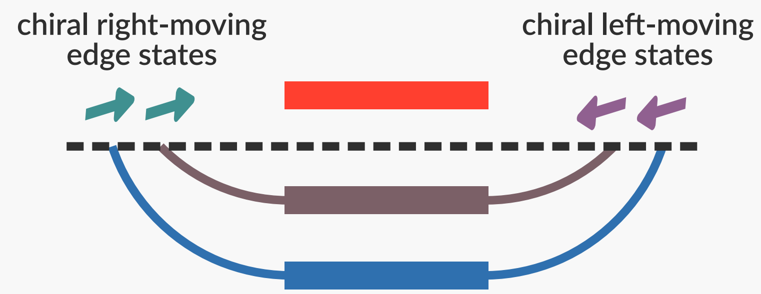


**FIG** 8: A schematic showing how edge states emerge from Landau levels and contribute to quantized Hall conductance. The dashed line represents the chemical potential. Each filled Landau level below the chemical potential contributes one chiral edge channel (right-moving on one edge and left-moving on the other edge), leading to a quantized Hall current. Because the number of filled levels changes only when the chemical potential crosses a Landau level, the Hall conductance remains constant over a range of energies, resulting in quantized plateaus.

on the opposite edges of the sample, applying a hall voltage difference between the left and right states leads to a net current $I$ flowing along the edge of each Landau level. Because of the presence of energy gaps between the Landau levels, the number of Landau levels that are occupied (below the dashed line in Fig 8) **cannot change continuously, but can only increase by one each time the dashed line passes through the center of a Landau level**. If the number of Landau levels below the dashed line is $n$, there are $n$ such edge states that have electrons in them and hence contribute a current $nI$. The Hall resistance is the total Hall current divided by the Hall voltage $V$, which comes out to be $nI/V$, which is clearly quantised through the integer $n$.

## What's the topological invariant?

What is the role of topology in all of this? The quantisation arises owing to the robustness of two aspects:

- robustness of the gaps in the Landau level which ensures the number of edge states do not change smoothly but rather in discrete steps, and
- robustness of the chiral edge states that can carry the Hall current.

Both of these are consequences of the non-zero magnetic field, which sets the topology of the wavefunctions (the separation of left and right moving states at the two edges). The topology remains undisturbed under small deformations (such as changing, by small amounts, the magnetic field, size of the sample, the temperature or the disorder), and can only change under large deformations (such as switching off the magnetic field entirely or drastically reducing the system size).

Similar to the Euler characteristic which acted as a topological invariant for polyhedrons, **is there again an invariant in this context that sets the topology of the wavefunction**? In quantum mechanics, the state of an electron moving with a certain momentum is described by a **wavefunction** with a phase. As the momentum $\boldsymbol{k}$ changes, this phase can twist and evolve, and is captured by something called the **Berry curvature** $\Omega(\boldsymbol{k})$. But what does the Berry curvature have to do with the Hall conductivity? Well, it turns out that the Hall conductivity in two dimensions can be expressed as **the integral, in momentum space, of the Berry curvature** of the wavefunction - the more the wavefunction "curves" in momentum space, the more is the conductivity. [7]

What does this have to do with topological quantisation? It can be shown that the integral of the Berry curvature is **always an integer multiple** of $2\pi$:

$$\iint_{\mathrm{MS}} \Omega(\boldsymbol{k})\,\mathrm{d}\boldsymbol{k} = 2\pi C, \quad C \in \mathbb{Z} \quad ,$$

where the integral is over momentum spac (MS), $\mathrm{d}\boldsymbol{k}$ represents the differential area in momentum space and $\Omega(\boldsymbol{k})$ is the Berry curvature at any point, acting as the integrand. **The quantised nature is reflected in the fact that $C$ (on the right hand side of the equation) is necessarily an integer**. This is analogous to the way the total curvature of a closed curve in 2D geometry - say, walking around a point - always adds up to an integer multiple of 2π, depending on how many times the path winds around that point (Fig 9). Similarly, the Berry curvature accumulates in momentum space, and its total integral - the **Chern number ($C$)- counts how many times the quantum wavefunction twists or "wraps" around the space of momenta**. This argument therefore links the Hall conductivity to the Chern number:

$$\sigma_H = C\frac{e^2}{h}$$

The Chern number is a **topological invariant**; it is insensitive to local details of the wavefunction and only depends on how many times the wavefunction wraps around in momentum space. This topological nature of the Chern number explains the robustness of the Hall conductivity: **it cannot change gradually as experimental conditions**

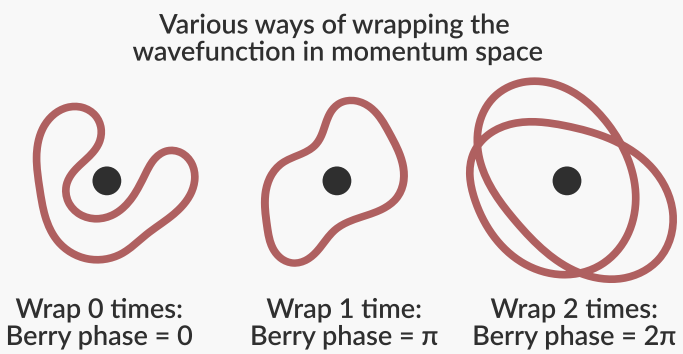


**FIG** 9: Visual representation of the geometric phase (Berry phase) acquired by a quantum wavefunction as its momentum traces a closed loop in momentum space. The central point represents a singularity in momentum space created by the magnetic field. The number of times the wavefunction's path wraps around this singularity determines the accumulated Berry phase - 0, π, or 2π in the examples shown. The total winding over the Brillouin zone gives an integer topological invariant known as the Chern number, which dictates quantized physical observables like the Hall conductance.

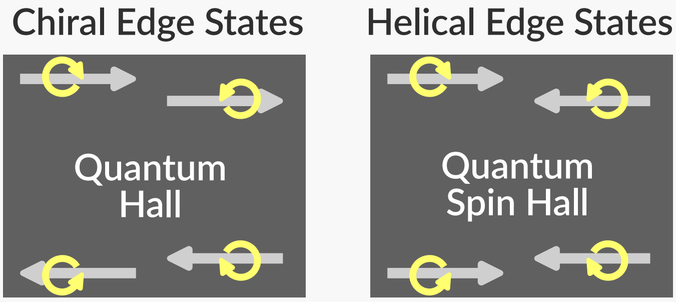


**FIG** 10: Comparison of the edge state structures in two topological systems. Left: In the quantum Hall effect, chiral edge states carry charge in a single direction along each edge, determined by the magnetic field. All current flows unidirectionally on a given edge, and backscattering is suppressed by spatial separation. Right: In the quantum spin Hall effect, helical edge states consist of counter-propagating modes with opposite spins on each edge. These states are protected by time-reversal symmetry and immune to backscattering from non-magnetic impurities, enabling dissipationless spin-polarised transport.

**are tweaked**. Instead, it only jumps when the system undergoes a true topological transition - such as when the chemical potential crosses a Landau level and a new chiral edge state emerges. This is why the plateaus are sharp and stable: **they reflect changes in an integer-valued invariant that counts how the wavefunction "winds" in momentum space** [8].

## Beyond quantum hall: Topological insulators

While the quantum Hall effect relies on the breaking of time-reversal symmetry (TRS) to generate its chiral edge states and quantized conductance, physicists have discovered materials, referred to as **topological insulators** [9], that can support topologically-protected edge states even in the **absence of any external magnetic field**. Instead of a magnetic field, these materials require **strong spin-orbit coupling** (SOC) - an effect where an electron's motion through the crystal lattice is intimately linked to its intrinsic angular momentum (spin). In fact, SOC acts like an internal, spin-dependent magnetic field, but one that **does not break TRS**. The presence of SOC gives rise to **helical edge states**: at each edge, electrons of opposite spin travel in opposite directions. This mechanism filters out spin-up and spin-down electrons into opposite directions at the edges, forming spin-polarized, counter-propagating states at each edge - a hallmark of the **quantum spin Hall effect** (Fig 10).

Importantly, due to TRS, **backscattering between the opposite spin states at each edge is prohibited**; such a scattering process is not allowed by the symmetry. This makes these edge channels robust against non-magnetic disorder (magnetic disorder will allow scattering between the opposite spin channels at each edge). The edges of a topological insulator exhibit **perfect transport**, meaning no energy is lost as heat, and the number of conducting pathways can be tuned. Though measuring spin currents is more subtle than charge currents, advanced experimental techniques have made such measurements possible, confirming the presence of spin transport along the edges.

## Topology meets technology: The promise of topological qubits

A natural question arises: why should we care about the topological properties of quantum systems? One compelling answer lies in **quantum computing**!

Quantum computers leverage the unique property of quantum particles to exist in multiple states simultaneously (**superposition**) to store information in qubits. This enables them to solve problems **exponentially faster** than classical computers, which rely on classical bits (which are either 0 or 1). The main challenge in this approach is that qubits are **extremely fragile** - tiny interactions with the environment can decohere the information, leading to errors in computation.

**Topological quantum computation** addresses this by using topological qubits that encode information not in the precise configuration of a system, but in its topological properties - features that are preserved under continuous deformation [10]. One approach towards this is by using **anyons** - exotic emergent

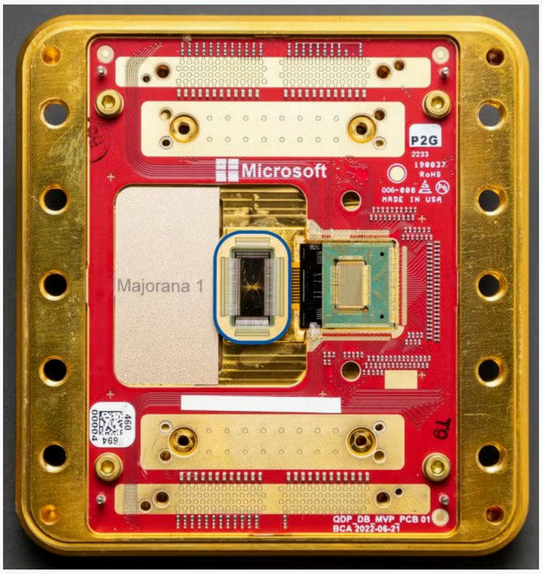


**FIG** 11: Microsoft's "Majorana 1" chip, an experimental platform designed to probe topological superconductivity. The chip architecture supports bound states consistent with spatially separated Majorana modes, which could serve as building blocks for topological qubits. This marks a major step toward realizing fault-tolerant quantum computation grounded in the topological robustness of quantum states where information is stored not in physical configurations, but in the winding and braiding of emergent excitations.

particles that appear in two dimensions. The collective quantum state of such systems depends on **global properties** such as the winding pattern of the anyons around each other (a process known as braiding), and is independent of the precise geometric or local details [11]. This topological nature of the quantum state makes the system inherently robust against local disturbances or errors, providing a promising foundation for **fault-tolerant quantum computation** [12].

Several platforms are being explored to realize these ideas, including systems based on **Majorana modes** [13]. Recently, Microsoft published a study in Nature that carries out measurements on a topological superconductor [14] (Fig 11). In **topological superconductors**, it is theorised that the lowest-energy excitation corresponds to a single electron being nonlocally stored between two spatially separated Majorana modes. Microsoft's results show evidence for an extra electron occupying a low-energy bound state, consistent with theoretical predictions for a Majorana mode. While the report is not unequivocal in the demonstration of the topological Majorana modes and does not rule out non-topological explanations, it highly constrains such non-topological states and advances the field of topological computation in a concrete way by demonstrating that such measurements are certainly consistent with topological computation.

While the full experimental verification of Majorana-based qubits remains an ongoing challenge - previous claims have been met with skepticism and rigorous scrutiny - Microsoft's results are a tangible step forward in the quest to harness topological phases of matter for real-world quantum computing. If successful, it would validate years of theoretical predictions and could signal a turning point where topology moves from abstract mathematics into the heart of practical, next-generation technologies.

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# Solar Energy and Weather


## Dr. Manohar Lal (Associate Professor, Indian Institute of Geomagnetism)


**Did you know the Sun isn't just lighting our days - it's also powering our weather forecasts and solar panels?** While sunspots and solar flares barely tweak sunlight's strength, they can actually nudge our climate; think rain patterns shifting or dry spells settling in. Imagine if, by tracking those solar signals, we could better predict cloudy days or droughts, making solar energy smarter and more reliable, and achieve sharper forecasts and greener power planning.

*Also available online, at scicomm.iiserkol.ac.in*


**REVIEWED BY**
Aranya Mukherjee and Sharanya Chatterjee

**SUBMITTED**
May 17, 2025

**CATEGORY**
Earth Science

**Dr. Manohar Lal** did his Master's degree in Physics from Gorakhpur University. He did his Ph.D. from Gujarat University (PRL), Ahmedabad. He did CSIR Research Associateship from NPL, New Delhi. He joined IIG Mumbai in 1996 as a Fellow and got superannuation in April 2025 from IIG as an Associate Professor.

The Sun is the ultimate driver of Earth's weather and climate. It plays a major role in heating the atmosphere, creating wind, influencing ocean currents, evaporation and rain, and seasonal changes. Solar radiation warms the Earth's surface, which in turn heats the air above it, creating temperature variations that drive weather patterns. The Sun warms ocean water unevenly, leading to currents that affect weather systems worldwide. Earth's tilt means sunlight intensity varies throughout the year, creating seasonal weather shifts.

Understanding solar energy and how it can be harnessed for human use is increasingly important. The Sun provides a consistent and renewable source of energy, but its availability at any given location depends on several atmospheric and climatic factors.

## Solar Energy and Weather Prediction

It has long been suspected that fluctuations in the energy output of the Sun may affect Earth's weather and climate. If we can understand the linking mechanisms of the phenomena, we may be able to solve several of man's most perplexing problems. For example, the critical role played by adverse weather and climate changes on world food supply has come into sharp focus in recent years. The ability to predict such changes with greater certainty than is now possible, especially the time and place of drought occurrence, could greatly improve global crop production schedules and thus alleviate incidences of famine.

Less attention has been paid to the impact of weather and climate on the effective utilization of solar energy. In its quest to make our nation self-sufficient for its energy needs, several agencies are examining the possibility of harnessing solar radiation. One of the most important variables that affect the utilization of solar energy is related to the weather and climate. The degree of cloud cover directly affects the amount of solar energy reaching solar collectors on the Earth's surface. Alternative energy sources such as wind energy must be trapped when there are many consecutive cloudy days. Since the meteorological and climatological parameters that affect solar energy use vary with time on both long and short term basis. It is evident that the demands on solar energy and the efficiency of its utilization will also vary with time.

To ensure maximum benefit from the energy source and to allow for efficient scheduling of alternate energy sources, variations in meteorological and climatological parameters must be predictable to a high degree of accuracy. The only way in which this state of affairs can be improved is to enhance the predictability of weather and climate. One key element that has been largely ignored and that we believe could be crucial to a better understanding and predictability of weather and climate is the possible influence of solar activity on meteorological and climatological parameters.

## What Is Solar Activity?

We use the term solar activity to distinguish the transient and energetic outbursts of solar energy from the more regular radiation often termed the solar constant. The basic measure of solar activity is the number of sunspots visible on the solar disk at any given time. The more spots, the more active the Sun is. An active Sun produces transient

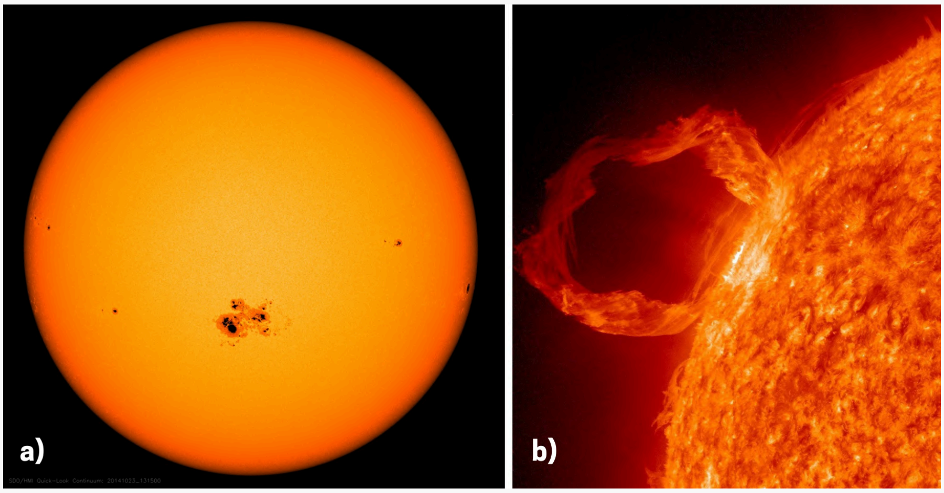



FIG 1: a) The black spots visible in the solar disk are the *Sun-spots*, which are the basic measure of solar activity.

b) Bursts of electromagnetic energy, *Solar-flares*, produced by an active Sun.

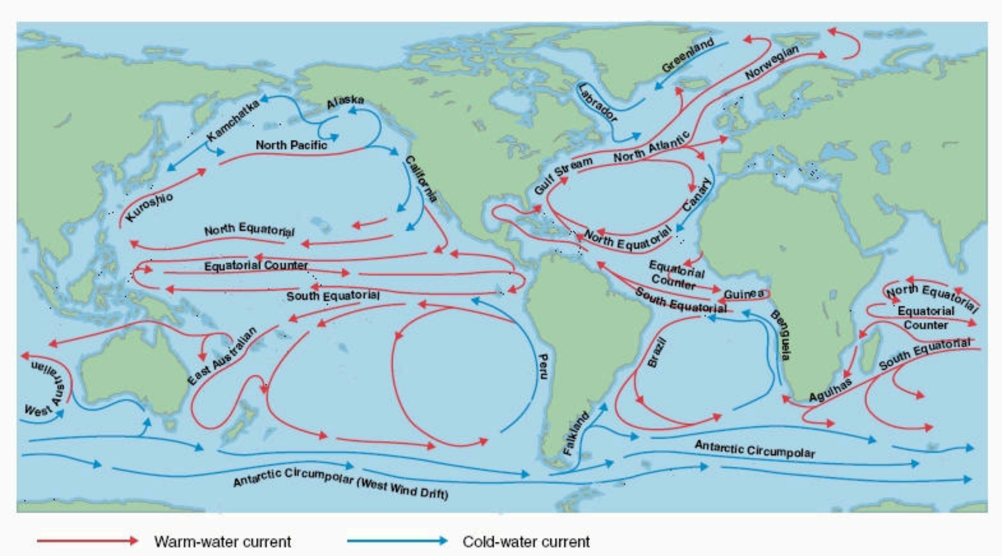



FIG 2: Ocean Circulation, redistributing heat from the equator to the poles, would bring changes in weather and climate.

events such as solar flares, which are bursts of electromagnetic energy in the visible, ultraviolet, and X-ray portions of the spectrum. A solar flare eruption may last from a few minutes to several hours and is sometimes accompanied by electromagnetic emissions in the microwave radio frequency range.

With large flares, the Sun often emits relativistic charged particles, protons, alpha particles, and electrons, sometimes referred to as solar cosmic rays. The most abundant charged particle is the solar proton. We use the term solar proton in preference to the term solar cosmic rays. In addition to solar energetic particles, Earth is continuously bombarded by high-energy particles from outside the solar system, known as galactic cosmic rays. Both types of particles can influence atmospheric chemistry and potentially cloud formation, which may in turn affect weather and climate patterns.

## Other Cosmic and Terrestrial Forces

Some researchers believe that solar activity is not the only external driver of climate variability. Oceans, for instance, are thought to play a major role in redistributing heat from the equator to the poles. Changes in ocean temperatures and circulation would foster changes in atmospheric heat distribution and therefore in weather and climate.

Others have suggested that volcanic eruptions introduce widespread dust in the atmosphere that would block the Sun's rays, leading to a cooling trend, cloud formation, and greater rainfall. Changes in the area and extent of the polar ice caps may also force the world's climate to change. It has been postulated that the passage of the solar system through interstellar clouds might affect the Earth's climate.

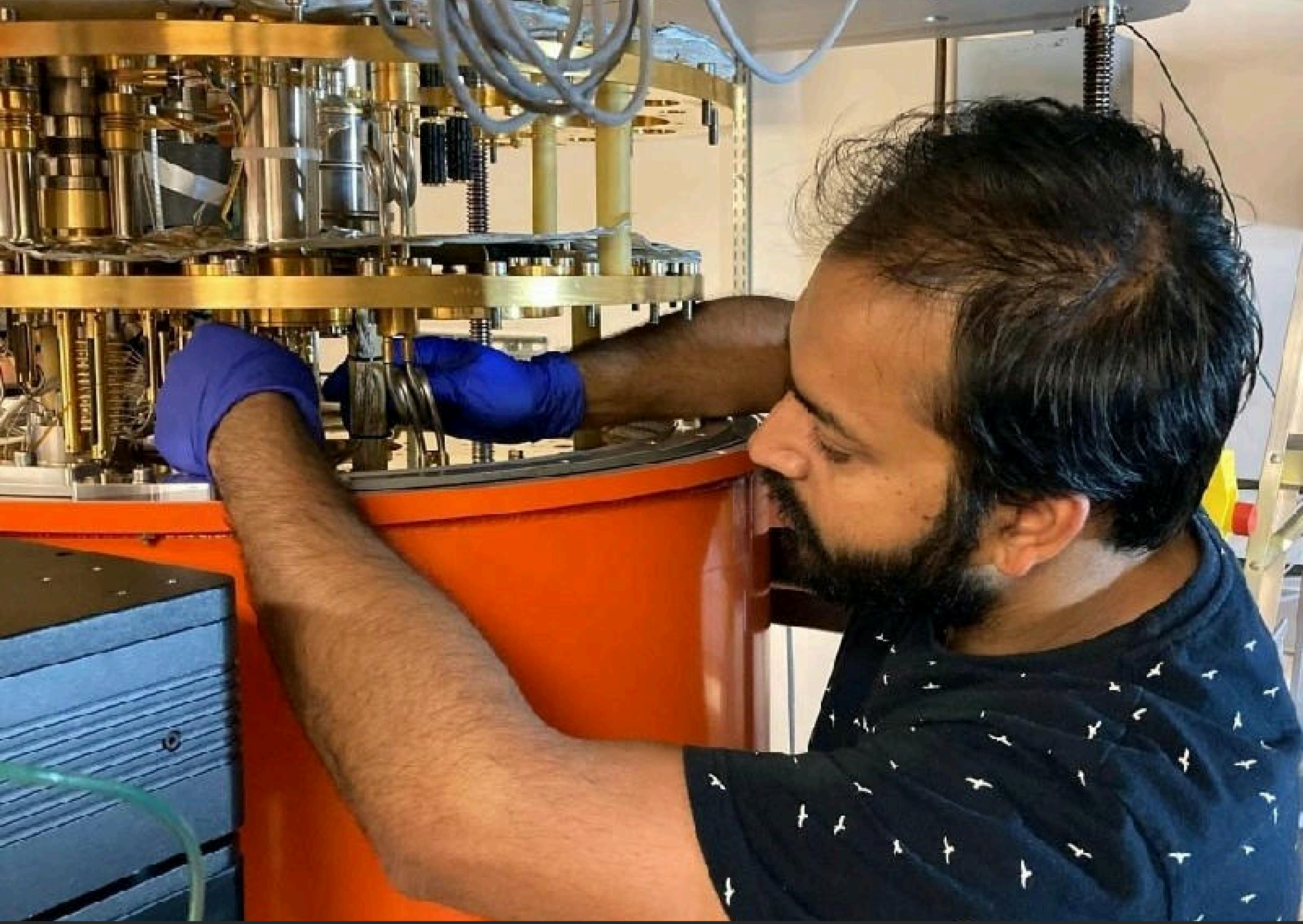
On longer timescales, changes in Earth's orbit and axial tilt affect the amount of solar energy received at different latitudes, potentially triggering glacial and interglacial periods. These orbital variations form the basis of Milankovitch cycles, which are key to understanding ice age dynamics.

## Conclusion: Can We Forecast the Sun's Whims?

Although the subject of Sun-Weather relationships has been studied for more than a century, there has to be more widespread acceptance of the results and to incorporate the results into weather forecasting or climate prediction methods. The main objection to this approach has been threefold:

1. Observed correlations between solar activity parameters and meteorological and climatological responses sometimes break down after several solar cycles.
2. More acceptable physical explanations needed of why there should be a causal relationship between activity on the Sun and terrestrial weather.
3. The amount of energy from the Sun due to solar activity is miniscule compared to the continuous radiant energy which is believed to be the driving force for our weather machine, meaning that solar activity should at best only trigger changes in the Earth's weather and climate.

Despite these challenges, there is potential for solar activity research to enhance our predictive capabilities in meteorology and climatology. With more rigorous scientific investigations, the influence of solar variability could eventually be incorporated into forecasting models, leading to better preparedness for weather-related impacts and more efficient use of solar energy resources.



# From IISER Kolkata Transit Campus to Tel Aviv: Rajarshi Bhattacharyya's Academic Voyage

Swarnendu Saha (IISER Kolkata)

*"Just try to self-teach yourself the thought process of training yourself to have an intelligent way of approaching any problem, as intelligently as possible."* says Rajarshi Bhattacharyya, experimental physicist and alumnus of IISER Kolkata (BS-MS, 2015), as he reflects on his academic journey from IISER to a PhD at the Weizmann Institute specialising in mesoscopic transport physics and quantum hall systems. He further dives into the hostel life during IISER's campus transition, compares global PhD systems, and urges students to value clear thinking over career labels.

*Also available online, at scicomm.iiserkol.ac.in*

**SS: Hello, I am Swarnendu Saha from InScight and today I invite you to this interview. Rather than thinking of this as an interview, please consider this as our attempt to understand how the present IISER Kolkata appears in the eyes and views of an alumnus.**

**RB:** Thank you Swarnendu. It is a great pleasure for me to meet you. And as I mentioned earlier, I also see this interview more as a platform of interaction rather than a so-called interview. And I am absolutely happy to share my experiences and address your questions about my experience and everything, basically everything that you have in mind. Please start.

**SS: I believe you joined here in 2010 and passed out in 2015. So, I think you did not see this building as a student.**

**RB:** (smiling) I did see this building as a student and I will tell you why. During my five years here in IISER Kolkata, in the beginning, there was a transit campus that was leased from BCKV. And at that time, around 2013, there was an active movement of moving the labs and everything on the infrastructure slowly towards this permanent campus.

The permanent campus was already in a build up phase during 2011-2012 and in 2013, the movement started. So, I lived both in the old campus and in the new, in different phases of my student life. Ishwar Chandra Vidya Sagar hostel was not there. at that time. So, in between the boys and the girls hostel, there was this canteen at the ground floor. And on top of the ground floor, there was lecture hall complex 4.

**SS: So, since you have actually seen, what the differences were of these two campuses and how the student life was different in both, if it was at all. And after 10 years, when you stand today, how is the difference?**

**RB:** Looking back about ten years to 2012–2013, the campus was in its developmental phase. The permanent campus was somewhat messy due to ongoing construction, whereas the transit campus, though more organised, was spatially constrained. Laboratory space and classrooms were notably small, leading to frequent complaints.

The transition to the permanent campus brought significant improvements, particularly with the large lecture hall complex, which could accommodate around 200 students. This was a stark contrast to the transit campus, where such capacity was impossible. In 2010, batch sizes were around 100, but by 2013–2014, they had exceeded 200, making the expanded facilities essential.

Another key difference was recreational space. The transit campus had some play areas, including a badminton court near AJC Bose Hall. There was also a popular tea stall and a small, shaded eating area, which were well-loved by students. A food outlet initially operated inside the transit campus before moving outside. These informal gathering spots were particularly cherished by many.

**SS: We had Bimalda, I mean we still have it, it is now in cafeteria form. I have seen Bimalda's old shop.**

**RB:** Right, right. But one thing that I can definitely say is the hostel life in the older campus at that time, at least that is what we realized, was really a little bit different than the hostel life in the new campus. It was a little bit more messy, but it was more enjoyable at the same time.

In the transit campus, student life felt more independent. The hostel was separate from the academic buildings, making it a space for personal activities like photography and other hobbies. Many students, especially nature photography enthusiasts, cherished this freedom and saw the hostel as their own space.

The transition to the permanent campus brought more organisation, but with that came restrictions—security regulations, permissions, and a structured environment. While this had its advantages, it also felt more constrained compared to the free-spirited days of the transit campus. It's similar to how

FIG 1: Rajarshi started his BS-MS classes in the transit campus of IISER Kolkata in 2010. [Source: alumni.iiserkol.ac.in]

people cherish music from their formative years—familiarity makes it special. For those who started in the transit campus, that environment holds a unique place in their hearts.

Looking at the permanent campus over time, it's now far more structured and truly resembles an IISER campus. In the early days, buildings were scattered, and not all facilities had moved from the transit campus. Today, everything is well-organised. Students likely appreciate this structure, with amenities like a badminton court inside the lecture hall complex.

On the way to the research hall complex, I also noticed a school, which had started earlier but is now fully operational. There are surely more changes I haven't explored yet, but the main transformation has been in the structured development of the campus.

**SS: Can you tell us briefly about your academic journey, starting from your schooling? I believe you carried out your doctoral studies in Israel. Israel is of course also in the news for the Israel-Gaza war. Can you please describe whether those issues affected you and your work?**

**RB:** My schooling was spread across different locations. Until Class 7, I studied at Barrackpore Mission, after which I moved to Malda Ramakrishna Mission for Classes 8 to 10 due to my father's transfer. Later, I returned to Barrackpore and completed my higher secondary education at Barrackpore Government School. After that, I joined IISER Kolkata, which played a crucial role in shaping my scientific interests. Unlike school, which primarily focused on syllabus-based learning and rote memorisation, IISER Kolkata provided my first real exposure to scientific experiments, critical thinking, and research methodologies. It was here that I truly understood how to think scientifically, a process that deeply influenced my decision to pursue research as a career. However, not all students from IISER Kolkata take the same path—many explore diverse career options beyond academia.

When considering a PhD, I had multiple offers from leading European institutions, including EPFL in Switzerland, Ulm University in Germany, and an institute in Israel. After evaluating my options, I chose Israel because the lab I was offered a position in was one of the best in its field. If you attend my talk, you might get a better sense of its significance. While I was aware of the regional conflicts, particularly the 2014 Israel-Gaza war, it did not deter my decision. A common misconception, especially in Bengal, was that Israel was a Muslim country due to its Middle Eastern location. In reality, Israel is a Jewish state, founded in 1948, with a distinct cultural and scientific identity. I even had to convince my parents by showing them evidence that it was not a Muslim-majority country.

Another key reason for choosing Israel was its strong reputation for scientific excellence. Around 27% of Nobel laureates over the past 50 years have been Jewish, despite Jews making up only 0.01% of the world's population. This reflects a strong intellectual culture where intelligence is not inherited but cultivated through rigorous training. Beyond research, what I truly gained in Israel was an invaluable approach to problem-solving. The mindset there is to face a problem, solve it, and move forward, rather than bypassing it. This systematic way of thinking extends beyond science and is deeply ingrained in their culture.

In summary, my journey from school to IISER Kolkata and eventually to Israel was driven by my passion for scientific exploration and a desire to develop a structured, problem-

FIG 2: Rajarshi in his BS-MS convocation ceremony with his MS guide Prof. Partha Mitra. [Source: www.facebook.com/rajarshi.bhattacharyya.35]

solving mindset. This experience has profoundly shaped my academic and intellectual growth.

**SS: Before going forward, I would request you to explain to our readers what your area of specialization is. How has that shaped you, and have you had a chance to maybe shape the field in some way?**

**RB:** Sure. Okay, again, this question has multiple parts, so I will try to split them up and then answer one by one. The first question is my area of specialization.

In a very, very broad category, it's experimental physics. If you try to narrow it down a little bit, it's condensed matter physics. If you narrow it down further, it's called mesoscopic physics.

Mesoscopic is basically a scale which is not really, which is not nanometer scale, which is neither nanometer scale nor microscopic scale. So, it's like, it's like a sub-microscopic scale and it's called mesoscopic basically, which means the samples that we deal with are of the order of, let's say, hundreds of nanometers to, let's say, a few micrometers, something like that. It's not angstrom scale, neither it's like a macroscopic scale. It's somewhere in between.

**SS: Since our magazine targets people from various backgrounds, can you please explain mesoscopic physics and its scale using a real world analogy?**

**RB:** That scale would be compared to, let's say, the diameter of our hair. I mean, that can vary depending on the strength of the hair. The diameter of typical hair is of the order of a few tens of micrometers.

Now, our scale starts at, let's say, around hundreds of nanometers and goes up to, let's say, hundreds of microns. So, it is within the, somewhat in the visible region? Not with the naked eye but yes, with the optical microscope, you can somewhat see it.

Of course, hundreds of nanometers or hundreds of nanometers, you can only probe it with, let's say, electron microscopy. So, that is my area of expertise and it is basically the scale that I talked about, now my particular area of expertise if you narrow it down further, it is called transport physics, where you basically make transport experiments on your system in the sense that you probe it using current and voltage measuring methods.

**SS: I guess what you mean to say is that when there is a transport before, after, during these phases you will see how the voltage and the currents vary and on the basis of this you go on further.**

**RB:** In my research, I focused on investigating phase transitions using transport experiments. This involves sending tiny electrical signals—either current or voltage—through a sample to probe phase transitions with high precision. If the signals were too strong, the transitions would blur out, making them difficult to study. These sensitive electronic experiments allowed me to explore energy scales relevant to phase transitions. My work was specifically centred around quantum Hall physics, a phenomenon best observed in two-dimensional heterostructures. While graphene research was growing at that time, 2D heterostructures remained one of the finest systems for studying the quantum Hall effect. However, these effects only manifest at extremely low temperatures, so all my measurements were conducted at temperatures as low as 10 millikelvin. You will see these temperature scales referenced in my talk as well.

Regarding how my PhD shaped me, I like to think of it as a rigorous training process. People may have different opinions, but in many ways, I find a PhD training comparable to army training. While army training disciplines the body and mind through physical and mental endurance, a PhD is a training of the intellect—a systematic process of learning how to think intelligently and approach problems in an analytical way. It is not just about the number of hours spent working in the lab; rather, it is about shaping the way one thinks and processes complex challenges.

Through this journey, I realised that a PhD is essentially a training of thought—an intellectual discipline that prepares one to tackle any problem, whether in research or beyond. I am particularly glad that I chose Israel for my PhD because, as I mentioned earlier, the mindset there is distinct. People, regardless of their profession, tend to address problems head-on, solve them, and then move forward. This approach left a deep impact on me, and I believe it is one of the most valuable aspects of my training.

**SS: If you don't mind me interrupting you, I would like to add something. Israel, after its birth, had to face many hurdles. I believe I am correct when I say that they have a minimum 2-3 years of mandatory military service, and you seem to be saying they have this mindset of solving any problems they face. If possible, they fully eliminate it. Do you think the experiences and history of the Israelites somehow shaped this mindset?**

**RB:** Absolutely. And maybe as you speak of it, it's possible that because even now in Israel it's a mandate that every citizen over there unless he is an orthodox Jew or have some other kind of disability or whatever has to mandatorily go through a military schedule like let's say at least he has to serve in the military for 2-3 years depending on the gender. This at a very early age for example after 18 and only after that people decide which direction to go like research or industry whatever or to do some further studies or whatever.

It's probably this military training that they get at this early age has quite some influence on them to develop this mindset of solving a problem one shot when they stumble upon something like that. So this thought process is definitely my PhD career over there. I would definitely, I can definitely see that development in myself about how to approach a problem, how to tackle a problem, how to even think about a problem and then step by step coming into the conclusion.

It's really something that comes from that training part. Of course it has another mix you get really a good exposure into research but these are things that everybody knows. Mostly it's a training period, that's what I would like to think about it.

The third part is how you would say that I might have shaped my particular field. I would say every PhD student shapes its field in one way or the other because a PhD, what does a PhD mean? A PhD means that you can think of it in a geographic way like let's say there's a circle of knowledge which is pre-existing and you are inside and your idea of doing the PhD while being inside the circle would be to expand the boundary no matter how small or how large it is. That is the idea. The moment you are able to expand the boundary of that knowledge you will be called a PhD. This is the ideal case.

Of course there are many different circumstantial issues that come into the picture but this is the ideal, this is the idea of being a PhD that the idea is that the moment you are able to push the boundary you are called a PhD. So in that sense I would say every single PhD in the world has shaped the particular field that they have worked on and I probably won't be an exception in that sense.

**SS: Moving on to other stuff, have a couple of short questions, particularly from the perspective of prospective PhD applicants. You applied to both Europe and Asia—specifically Israel—so how would you compare the application processes? How did the individual steps, such as CV preparation, contacting professors, and selecting an institute, differ between these regions?**

**I ask this with the hope that your insights will benefit future applicants. While students at IISER Kolkata are somewhat aware of opportunities in Israel, the most common choices for PhD aspirants tend to be the US as the primary target, followed by Europe. The order may sometimes vary, and occasionally, students consider Japan or Australia, though these are less common. However, Israel is not typically on the radar for many students outside IISER Kolkata. Even within IISER, interest in Israel as a PhD destination, while present, is comparatively lower.**

**RB:** The answer to this question is quite detailed, and I am not sure how much time we can allocate to it. However, I will try to keep it as concise as possible while providing my perspective.

One of the first things to consider when applying for a PhD is the choice of place—the lab you will be working in, the level of research, and the quality of work happening there. Unfortunately, after spending five years in IISER Kolkata, where students undergo rigorous coursework and gain some research exposure, they are suddenly confronted with the harsh realities of the outside world. These realities include multiple factors that influence the decision-making process.

For instance, if your long-term goal is to become an independent researcher—say, a faculty member in India—there are two main pathways to consider. The first is pursuing a PhD in India under a renowned professor who has a strong research output and a well-established lab culture. However, finding the right mentor in your specific area of expertise can be challenging. If you do secure a PhD position in such a lab, it can significantly boost your future career prospects because you will already be recognized in the research community during your PhD.

The second pathway is pursuing a PhD in a top lab anywhere in the world—whether in the US, Europe, Japan, or Israel. If you secure admission in a leading research group, the location does not matter. Ultimately, merit speaks for itself. However, securing a position in a top lab is not always easy, as availability depends on funding, timing, and competition. A lab might not have an opening when you apply, or you might not apply to the right lab at the right time. Being the right person in the right place at the right time is crucial for success.

If a candidate is unable to secure a position in a top-tier lab, practical considerations come into play. The structure of PhD programs varies significantly between different regions.

In Europe, PhD positions are often based on fixed-term contracts with a specific professor, typically lasting three to three-and-a-half years. Once the contract ends, the stipend stops—unless the professor has additional funding. This system requires students to complete their PhD within the contractual period, which can be a challenge. Moreover, in India, such short-duration PhDs are sometimes not considered equivalent to a full-fledged PhD. Since coursework is often minimal or absent in European PhD programs, these shorter PhDs may be perceived as premature or incomplete in the Indian academic system.

This is one of the reasons why many students prefer the US for PhD programs. The US PhD system follows a graduate school model, which provides a structured environment with coursework, research, and teaching assistantships over a typical


FIG 3: Rajarshi earned his PhD in condensed matter and material physics in the Weizmann Institute of Science, Israle. [Source: weizmann.ac.il]

duration of five to six years. In my case, I did not apply to the US primarily because of the GRE requirement, which I did not find to be a fair evaluation system at that time. That said, the US model has both advantages and disadvantages.

One challenge for PhD students in the US is that survival often requires additional work beyond research. Depending on the university and location, students may need to take on multiple responsibilities—such as teaching assistantships, coursework, and sometimes even part-time jobs—to sustain themselves financially. This extra workload can affect the quality of research, as students need to balance multiple commitments alongside their PhD work.

From this perspective, Israel offers a balance between the US and European systems. While European PhDs are shorter and contract-based, and US PhDs are longer but come with additional commitments, Israel falls in a sweet spot. The PhD structure in Israel provides adequate research time without the additional burden of extensive teaching or coursework requirements.

Additionally, for students from IISER Kolkata, there is another unique consideration. IISER students already graduate with a master's degree (BS-MS), but US PhD programs often do not require a master's degree for admission. This means that IISER students are technically overqualified when applying to US graduate schools, as they already possess a master's degree but would still be required to enroll in a program that includes a master's component.

That's why actually in RISC towards I think in 2011 or 2012, I don't recall exactly, they started a four-year BS program and that's very well suited for particularly for students who want to do a PhD in US, because they can do a four-year BS from here and then directly join a PhD there and get a master's degree together, okay. So, here you are giving it one more year, acquiring a master's degree and then you are going for a PhD, so it's this

FIG 4: Rajarshi at Submicron Center during his PhD in the Weizmann Institute of Science. [Source: www.facebook.com/rajarshi.bhattacharyya.35]

one year, it's there, that you are giving time to ISF Kolkata. So, yeah, all in all, this is basically, okay, so sorry, I was talking about Israel, why it's in a sweet spot is because it's not the contractual thing, so if you go to Israel, you will be guided for your PhD by a grad school system, apart from your own mentor for your PhD, there will be two other guides from the grad school system, who will overview your PhD work throughout the whole time.

**SS: That sounds like our practice of conducting research progress committee evaluations every year.**

**RB:** In Israel, the PhD system is somewhat similar to the graduate school model in the US, but with key differences. Two professors are typically assigned by the grad school system to oversee a student's PhD progress throughout their research. At the Weizmann Institute of Science, for example, the average time to complete a PhD is four and a half years. While I cannot confirm whether the same structure applies to other institutions like Hebrew University of Jerusalem or Technion, I do know that the overall PhD duration in Israel strikes a balance—it is neither as short as three years (as in some European programs) nor as long as six years (as in the US).

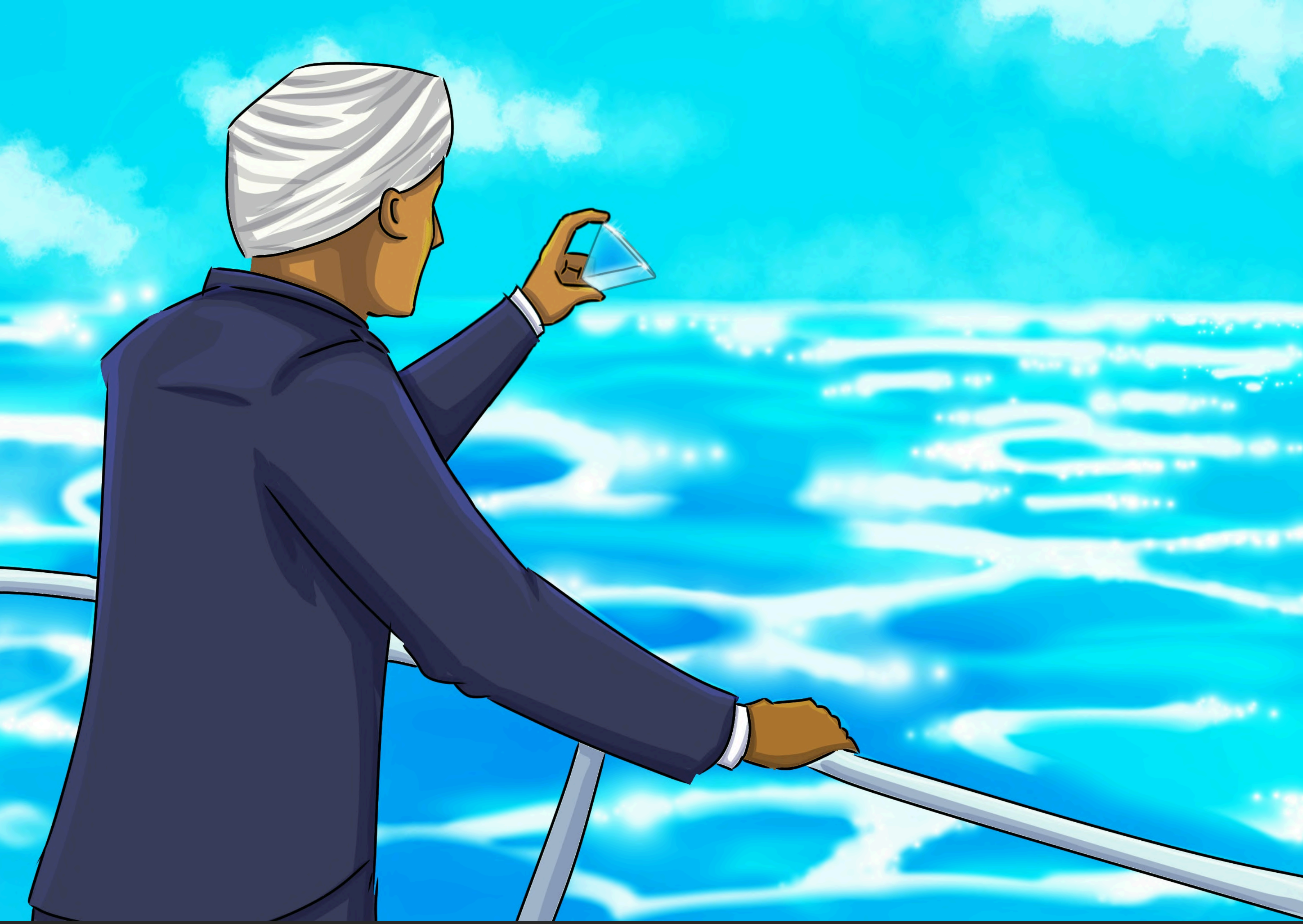
Another advantage of doing a PhD in Israel is the manageable coursework requirement. At Weizmann, students need to complete 12 credits, which typically translates to four to five courses over the entire PhD duration. This is relatively light compared to the coursework burden in the US. If a student chooses to complete these requirements within the first three years, it averages to about one and a half courses per year, leaving ample time for research.

Of course, given the current situation in Israel, prospective students might find it a difficult decision to pursue a PhD there. However, history has shown that tough times do not last forever, and I strongly believe that once this challenging period is over, the situation will stabilize. When I pursued my PhD in Israel, I was able to complete it peacefully without facing any major disruptions. I am confident that Israel, known for its resilience and innovation, will navigate through this phase successfully. The recovery is not a matter of five or ten years—things are already in motion, and stability will return soon.

**SS: Okay Dada, so it was nice to talk to you. Any last comments for our students?**

**RB:** I can wish them all the best for sure for their future endeavor, whatever career path you choose for yourself, it doesn't matter, you can choose PhD, you can choose MBA, you can choose to have your own business, whatever career path you choose, just try to self-teach yourself the thought process of training yourself to have an intelligent way of approaching any problem, as intelligently as possible. By saying as intelligently, it means saving as much time and resources and that basically, I mean your specific problem is your specific thing to solve, but this is the general thing that you will find that it would be very useful for yourself.

**SS: Thank you so much.**



# The Quest For The Sea's Blue: The Discovery of the Raman Effect


## Shreya Ganguly (IISER Kolkata)


Dicover how a simple question - why does the sea look blue - led to one of the most groundbreaking discoveries in physics. This engaging **science comic** traces C. V. Raman's journey to uncover the phenomenon that now bears his name.


***Shreya Ganguly*** *is a student of 22MS batch pursuing a physics major at IISER Kolkata. A habitual explorer and art-lover, she likes drawing, dancing and trying out her hand at graphic design and video editing - when she isn't drowning in coursework, that is.*

# A QUEST FOR THE SEA'S BLUE

## THE DISCOVERY OF THE RAMAN EFFECT

WHY DOES THE SEA LOOK BLUE? A YOUNG INDIAN PHYSICIST'S PURSUIT OF THIS ONE ANSWER WOULD SPIRAL INTO SOMETHING FAR GREATER - A DISCOVERY THAT WOULD GO ON TO LAY THE FOUNDATION FOR ALL MODERN DEVELOPMENTS IN MOLECULAR STUDIES AND SPECTROSCOPY.

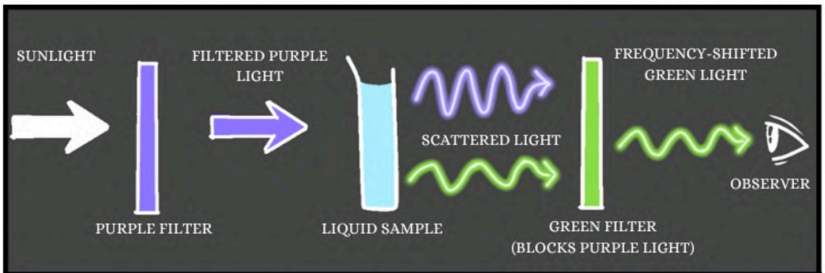
THIS IS THE STORY OF SIR CHANDRASEKHARA VENKATA RAMAN, AND THE GROUND-BREAKING DISCOVERY THAT CAME TO BEAR HIS NAME - THE RAMAN EFFECT.

BORN IN TRICHINOPOLY IN 1888, RAMAN CAME TO CALCUTTA IN 1907 TO JOIN THE INDIAN FINANCE SERVICES, LATER LEAVING TO JOIN RAJABAZAR SCIENCE COLLEGE AS PALIT PROFESSOR OF PHYSICS. ALL THE WHILE, HE CONTINUED HIS EXPERIMENTAL RESEARCH IN ACOUSTICS AND OPTICS AT THE INDIAN ASSOCIATION FOR THE CULTIVATION OF SCIENCES, CALCUTTA, FROM 1907 TILL 1933.

IT WAS 1921 - RAMAN WAS ON HIS WAY BACK FROM THE CONGRESS OF UNIVERSITIES OF THE BRITISH EMPIRE, OXFORD, ABOARD THE S.S. NARKUNDA.
HE NOTICED THE VIBRANT BLUE OPALESCENCE OF THE MEDITERRANEAN SEA AND BEGAN PONDERING - WHAT GAVE THE SEA ITS STRIKING HUE?

HE WAS NOT CONVINCED THAT THE BLUE WAS SIMPLY A REFLECTION OF THE SKY, WHICH WAS THE PREVAILING EXPLANATION BY LORD RAYLEIGH AT THE TIME.

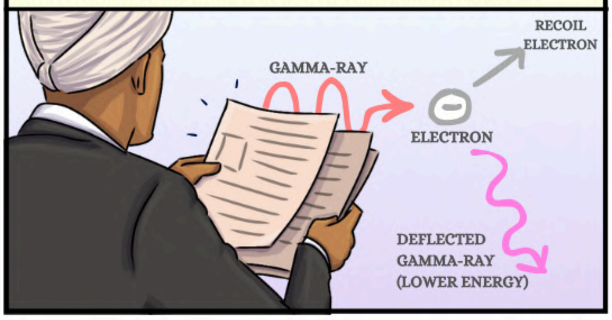
LIKE THE TRUE EXPERIMENTALIST THAT HE WAS, RAMAN PULLED OUT A POLARIZING NICOL PRISM FROM HIS POCKET.
QUENCHING THE REFLECTED LIGHT FROM THE SKY, HE NOTED THAT THE SEA'S BLUE HUE WAS UNATTENUATED - THE BLUE COLOUR WAS NOT MERELY A REFLECTION!
HE HAD A CONVICTION THAT WATER MOLECULES COULD SCATTER LIGHT, JUST AS AIR MOLECULES DID.
AS SOON AS THE SHIP REACHED BOMBAY, HE SENT A LETTER TO NATURE .

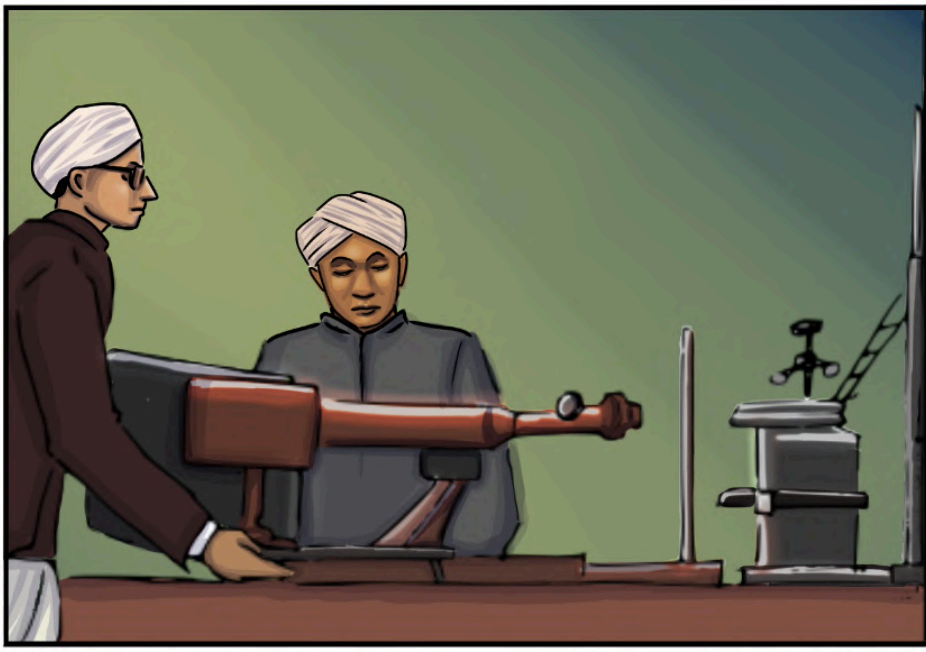



RAMAN'S RESEARCH GROUP AT IACS NOW EMBARKED UPON STUDYING LIGHT SCATTERING IN LIQUIDS.
THEIR SETUP WAS SIMPLE. LIGHT FROM A SOURCE - INITIALLY PLAIN SUNLIGHT, AND THEN SUNLIGHT CONCENTRATED USING A REFRACTING TELESCOPE - WAS PASSED THROUGH A COLOURED FILTER AND THEN MADE TO SCATTER OFF A LIQUID SAMPLE. OBSERVATIONS ON THE SCATTERED LIGHT WERE ALL CARRIED OUT BY EYE.

THEY TESTED OVER 60 DIFFERENT LIQUIDS AS WELL AS SOME SOLIDS, AND OBSERVED THE SAME WEAK, BUT UNDENIABLE EFFECT – THERE WAS A SHIFT IN THE COLOUR OF SOME OF THE SCATTERED LIGHT.

RAMAN'S COLLEAGUES INITIALLY DISMISSED THE PHENOMENON AS A FAINT TRACE OF FLUORESCENCE. HE, HOWEVER, HAD A DIFFERENT HUNCH.
IN 1922, ARTHUR HOLLY COMPTON HAD DISCOVERED THE "COMPTON EFFECT" - INELASTIC SCATTERING OF X-RAYS BY ELECTRONS. RAMAN SUSPECTED THAT SOME SIMILAR OCCURRENCE IN VISIBLE LIGHT MIGHT BE AT PLAY HERE, UNDERLYING THEIR STRANGE OBSERVATION.



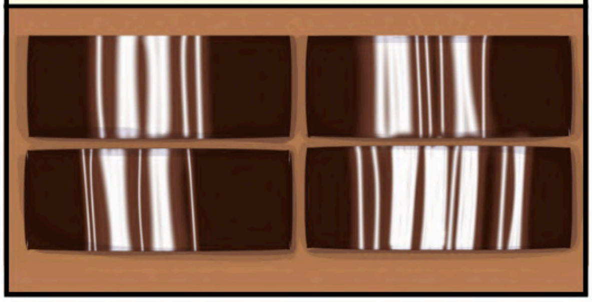


ALTHOUGH THE THEORETICAL IDEAS WERE STILL FUZZY, THE EVIDENCE FOR LIGHT SCATTERING IN BOTH LIQUIDS AND SOLIDS WAS CLEAR BY NOW.
RAMAN AND HIS COLLEAGUE K.S. KRISHNAN NOW SET OUT TO RIGOROUSLY VALIDATE THE FREQUENCY SHIFT THEY HAD OBSERVED, USING A HANDHELD POCKET SPECTROSCOPE.

FINALLY, THEY IMPORTED AND SET UP A QUARTZ SPECTROGRAPH, WITH WHICH THEY COULD CAPTURE THE SPECTRUM OF THE SCATTERED LIGHT, USING A MERCURY ARC LAMP AS THEIR LIGHT SOURCE.
RAMAN IS SAID TO HAVE REMARKED REGARDING THE SPECTROGRAPH, "WITH THIS, I BELIEVE I CAN GET A NOBEL PRIZE FOR INDIA."

SURE ENOUGH, THE PHOTOGRAPHIC PLATES FROM THE SPECTROGRAPH SHOWED FAINT, BUT DISTINCT, EMISSION LINES ON EITHER SIDE OF THE ELASTICALLY SCATTERED RAYLEIGH LINES.

FINALLY, ON FEBRUARY 28, 1928, THEY OBSERVED THAT THE SCATTERED LIGHT WAS POLARIZED, DISTINGUISHING THE OBSERVED EFFECT FROM FLUORESCENCE WITH CERTAINTY.
RAMAN'S SUSPICIONS WERE PROVEN TRUE - THIS WAS INDEED A NEW PHENOMENON, INELASTIC SCATTERING OF VISIBLE LIGHT!



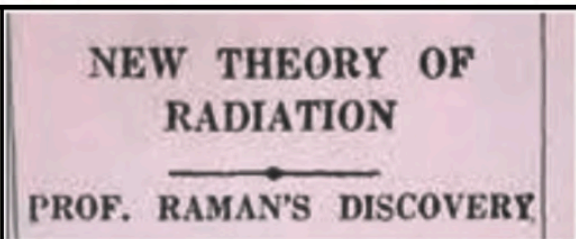

RAMAN AND KRISHNAN SENT OFF A SHORT PAPER TO NATURE, TITLED "A NEW TYPE OF SECONDARY RADIATION", BRIEFING THEIR RESULTS AND THE NEW DISCOVERY. IT WAS PUBLISHED ON MARCH 31, 1928.

RAMAN FIRST PRESENTED THEIR QUANTITATIVE MEASUREMENTS ON MARCH 16, IN HIS LECTURE TO THE SOUTH INDIAN SCIENCE ASSOCIATION. THE RESULTS, INCLUDING THE SPECTRAL DATA, WERE DETAILED IN RAMAN'S PAPER IN THE INDIAN JOURNAL OF PHYSICS, PUBLISHED IN APRIL 1928.

THE NEWS OF RAMAN'S DISCOVERY SENT WAVES THROUGH THE PHYSICS COMMUNITY. PHYSICISTS RECOGNIZED ITS SIGNIFICANCE IN THE ERSTWHILE NEWLY-DEVELOPING QUANTUM THEORY OF LIGHT. SEVERAL SCIENTISTS REPRODUCED AND STUDIED "THE RAMAN EFFECT" IN THE FOLLOWING YEARS.

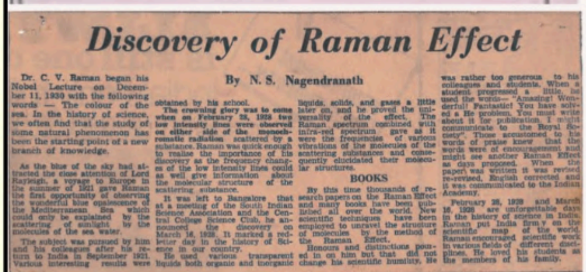
IN RUSSIA, MANDELSTAM AND LANDSBERG HAD ALSO INDEPENDENTLY FOUND THE SAME EFFECT IN QUARTZ CRYSTALS AROUND THE SAME TIME, BUT THEIR WORK WAS PUBLISHED LATER, IN JULY 1928.

FINALLY, IN 1930, SIR C.V. RAMAN WON THE NOBEL PRIZE IN PHYSICS - THE FIRST NON-WHITE SCIENTIST, AND SO FAR THE ONLY INDIAN SCIENTIST, TO EVER HAVE WON A NOBEL FOR A SCIENTIFIC DISCOVERY.



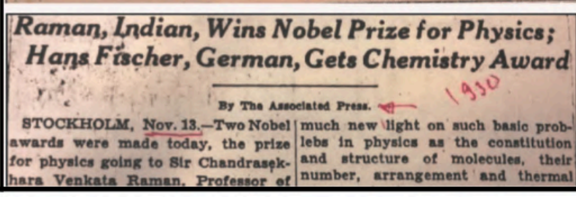
NEW THEORY OF RADIATION

PROF. RAMAN'S DISCOVERY



Discovery of Raman Effect

By N. S. Nagendranath

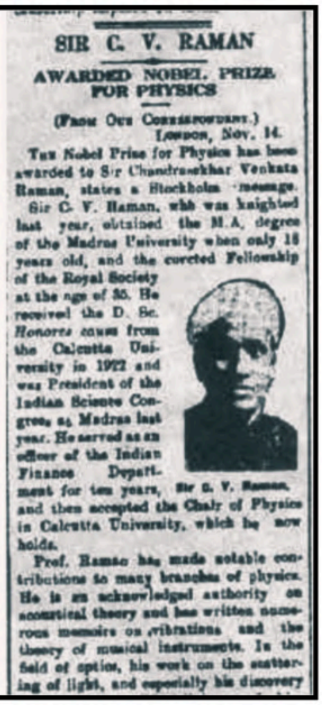


Raman, Indian, Wins Nobel Prize for Physics; Hans Fischer, German, Gets Chemistry Award

By The Associated Press.



STOCKHOLM, Nov. 13.—Two Nobel awards were made today, the prize for physics going to Sir Chandrasekhara Venkata Raman, Professor of much new light on such basic problems in physics as the constitution and structure of molecules, their number, arrangement and thermal



SIR C. V. RAMAN

AWARDED NOBEL PRIZE FOR PHYSICS

(FROM OUR CORRESPONDENT.)
LONDON, Nov. 14.

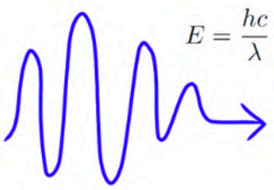
The Nobel Prize for Physics has been awarded to Sir Chandrasekhar Venkata Raman, states a Stockholm message.

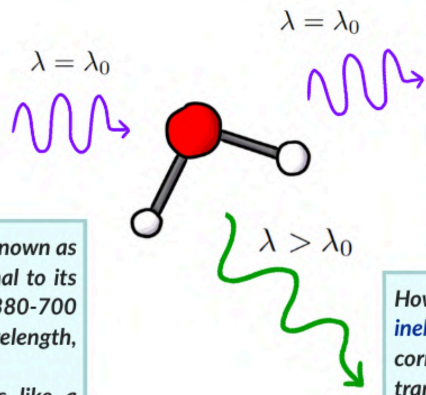
Sir C. V. Raman, who was knighted last year, obtained the M.A. degree of the Madras University when only 18 years old, and the coveted Fellowship of the Royal Society at the age of 35. He received the D. Sc. *Honoris causa* from the Calcutta University in 1922 and was President of the Indian Science Congress at Madras last year. He served as an officer of the Indian Finance Department for ten years, and then accepted the Chair of Physics in Calcutta University, which he now holds.

Sir C. V. Raman.

Prof. Raman has made notable contributions to many branches of physics. He is an acknowledged authority on acoustical theory and has written numerous memoirs on vibrations and the theory of musical instruments. In the field of optics, his work on the scattering of light, and especially his discovery

## WHAT IS THE RAMAN EFFECT - AND WHY IS IT SO SIGNIFICANT?

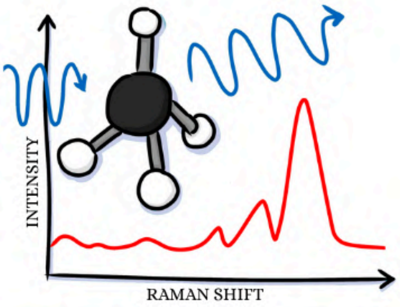



*Light travels in the form of discrete wave-packets known as photons. A photon's energy is inversely proportional to its wavelength. The colour of visible light (380-700 nanometres) is determined by its frequency or wavelength, and thus directly by its energy.*
*When light is incident upon matter, it behaves like a stream of particles. Upon striking a molecule, photons interact with it and get deflected at different angles. This is the phenomenon of scattering.*

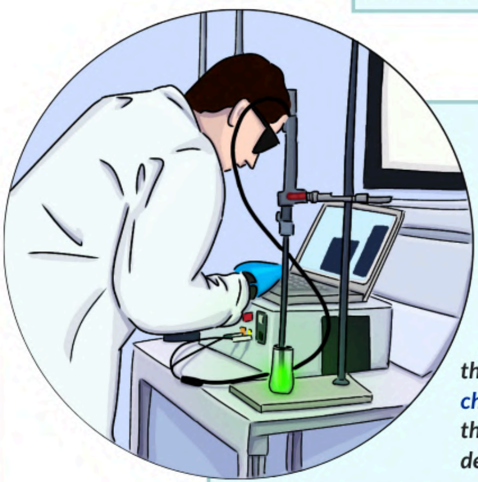
*Most of these scattering events are elastic - the collisions do not result in any transfer of energy between the photon and the molecule.*
*The deflected photon has the same frequency as the incident state, hence the scattered light has the same colour.*
*This is known as Rayleigh scattering.*

*However, a small fraction of these collisions are inelastic, i.e. they result in energy transfer - corresponding to rotational and vibrational transitions in the molecule.*
*Thus, some photons are deflected with a higher or lower energy, giving a different colour to a fraction of the scattered light. This is the phenomenon of Raman scattering, or the Raman effect.*
*This was why, in Raman's early light-scattering experiments on liquids, a part of the purple filtered sunlight was scattered as green.*




*The discovery of the Raman effect provided experimental support for the theory of discrete light quanta, as well as for quantum transitions between molecular energy levels. The theoretical implication was profound - the Raman shifts in light scattered from a molecule were a direct imprint of its vibrational energy levels.*

*The Raman shift plotted against intensity of the scattered light is known as the Raman spectrum. The Raman spectrum is unique for a given kind of molecule, which is why it is known as a "molecular fingerprint".*



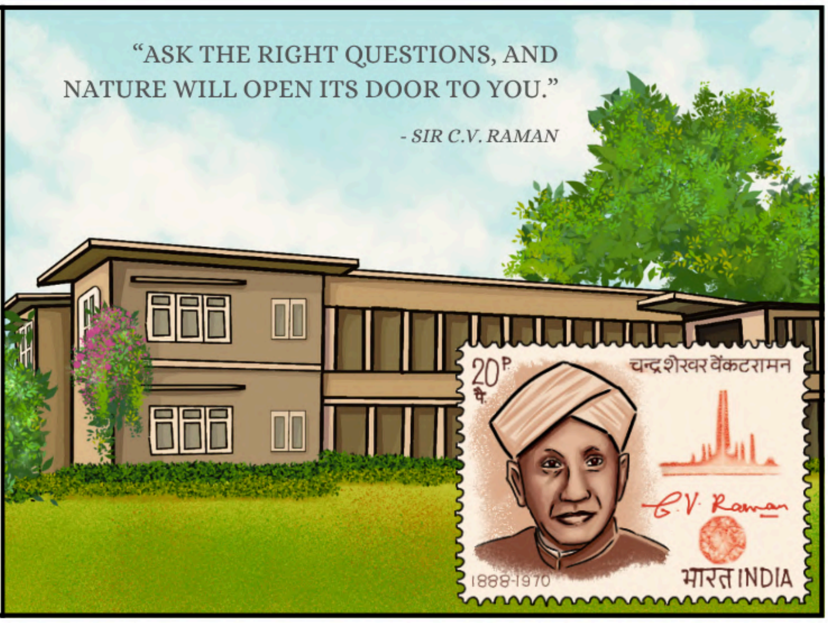
*With the invention of the laser as a coherent monochromatic light source in the 1960s, the Raman spectra of molecules could now be captured and studied in high resolution, providing the first impetus to the development of Raman spectroscopy. Analysis of the Raman spectra allowed for characterisation of substances based on their "molecular fingerprint", and thus detection of their chemical composition.*

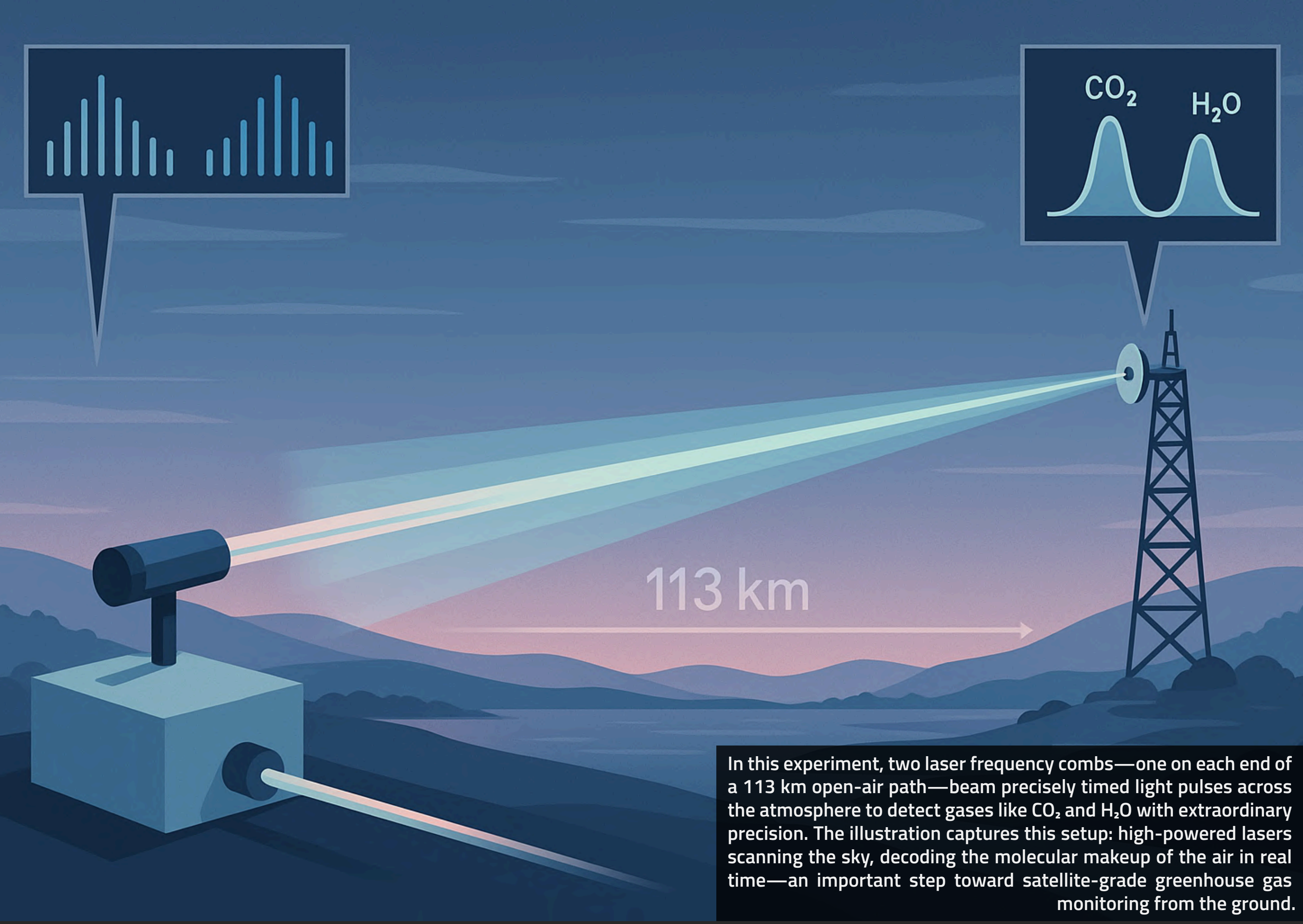
*Today, this principle finds application in technologies like Raman spectroscopes, confocal Raman microscopes, Raman scanners, etc. which are widely used for a multitude of detection, identification and characterisation purposes across diverse fields, ranging from healthcare, to forensics, to industrial chemistry, to materials science research.*

*RAMAN RECEIVED SEVERAL MORE HONOURS FOR HIS CONTRIBUTIONS TO PHYSICAL SCIENCE, INCLUDING THE KNIGHTHOOD FROM THE BRITISH EMPIRE IN 1929, AND THE BHARAT RATNA IN 1954.*

*HE BECAME THE FIRST INDIAN DIRECTOR OF THE INDIAN INSTITUTE OF SCIENCE, BANGALORE, SERVING FROM 1933 TILL 1948, AFTER WHICH HE WENT ON TO ESTABLISH THE RAMAN RESEARCH INSTITUTE IN THE SAME CITY, WHERE HE CONTINUED HIS SCIENTIFIC WORK TILL THE END OF HIS LIFE.*

*TO COMMEMORATE RAMAN'S DISCOVERY, 28TH FEBRUARY IS OBSERVED AS NATIONAL SCIENCE DAY IN INDIA EVERY YEAR. ALMOST A CENTURY ON, SIR C.V. RAMAN'S LEGACY REMAINS A BEACON OF SCIENTIFIC CURIOSITY AND EXCELLENCE, INSPIRING GENERATIONS OF SCIENTIFIC MINDS TILL DATE.*






In this experiment, two laser frequency combs—one on each end of a 113 km open-air path—beam precisely timed light pulses across the atmosphere to detect gases like $CO_2$ and $H_2O$ with extraordinary precision. The illustration captures this setup: high-powered lasers scanning the sky, decoding the molecular makeup of the air in real time—an important step toward satellite-grade greenhouse gas monitoring from the ground.

# Insight Digest

## Fresh highlights from the frontiers of science

**Debanuj Chatterjee** Fast and precise atmospheric sensing over 100 km open path

**Chitradeep Saha** Tree rings unlock the sun's age old secrets

**Madhura Narayan Joshi** How does Antarctic sea ice and circulation change fate of global $CO_2$ levels

**Swarnendu Saha** Old carbon routed from land to the atmosphere by global river systems

*Also available online, at scicomm.iiserkol.ac.in*

# Fast and precise atmospheric sensing over 100 km open path

Han, JJ., Zhong, W., Zhao, RC. et al. Nat. Photon. 18, 1195–1202 (2024)

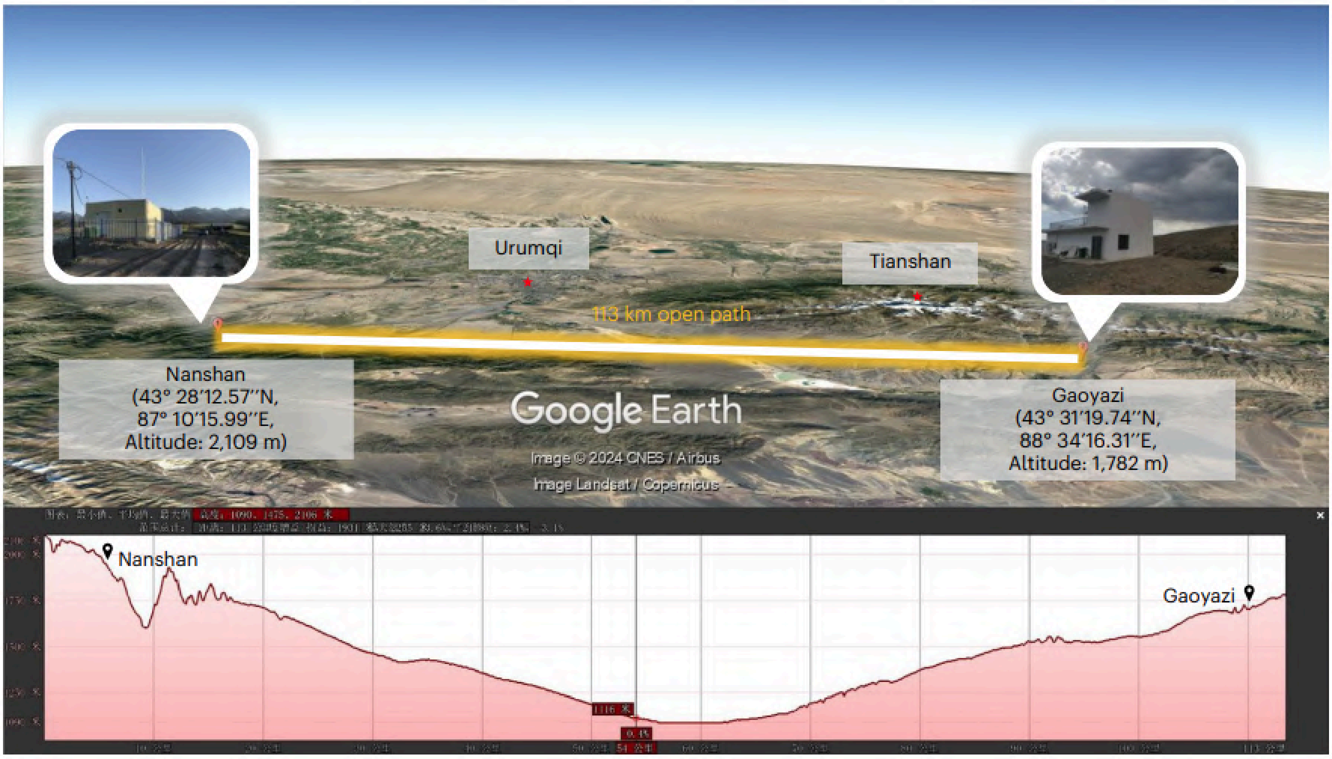
Contributed by **Debanuj Chatterjee (University of Lille, France)**

Dual comb spectroscopy (DCS) is a powerful optical sensing technique that leverages two laser frequency combs, to measure gas absorption with high speed and sensitivity. By precisely determining the absorption frequencies of the sample, across a broad spectral range, DCS can detect trace gases like carbon dioxide ($CO_2$) and water vapor ($H_2O$) in the atmosphere with sub-ppm precision. This makes it ideal for applications in climate science, especially relevant for air quality monitoring, greenhouse gas emissions tracking, etc.

Traditionally, the reach of DCS when performed in open path has been limited to distances under 20 km due to significant signal loss and technical constraints, such as the need for highly reflective mirrors, high atmospheric turbulence, etc. However, last year, in a landmark advancement, researchers from the University of Science and Technology of China have now extended DCS to a staggering 113 km open-air horizontal path; nearly six times longer than previous records.

To achieve this, the team utilized a novel bistatic configuration, placing one frequency comb at each end of the path and transmitting light bidirectionally through the atmosphere without the need for reflectors. Each comb was synchronized to a rubidium atomic clock, acting as a local timing reference. The system incorporated high-power (1 W) optical frequency combs, stable telescopes, and real-time data acquisition to overcome atmospheric turbulence and extreme signal attenuation, going up to 83 dB.The experiment, conducted between two mountain sites in the Xinjiang, provice of China viz. Nanshan and Gaoyazi, successfully measured absorption spectra of $CO_2$ and $H_2O$ over a 7 nm bandwidth and a frequency accuracy of 10 kHz. The system achieved $CO_2$ detection sensitivities better than 2 ppm in just 5 minutes and below 0.6 ppm in 36 minutes; a remarkable performance for such a long-range setup.

This breakthrough not only validates DCS for ultra-long-range sensing but also opens a plethora of possibilities for a diverse set of technological advancements. A curious reader would ask if one can perform DCS over 100 km path in the turbulent atmosphere, why not shoot it towards the sky? Can the dual comb reach the ionosphere (50 km) and get reflected with only the radio wave content? Can it lay the foundation for future satellite-ground dual comb links? Can it perform high-precision monitoring of greenhouse gases from geostationary orbits? I leave the numerous possibilities to the fancy of your imagination!



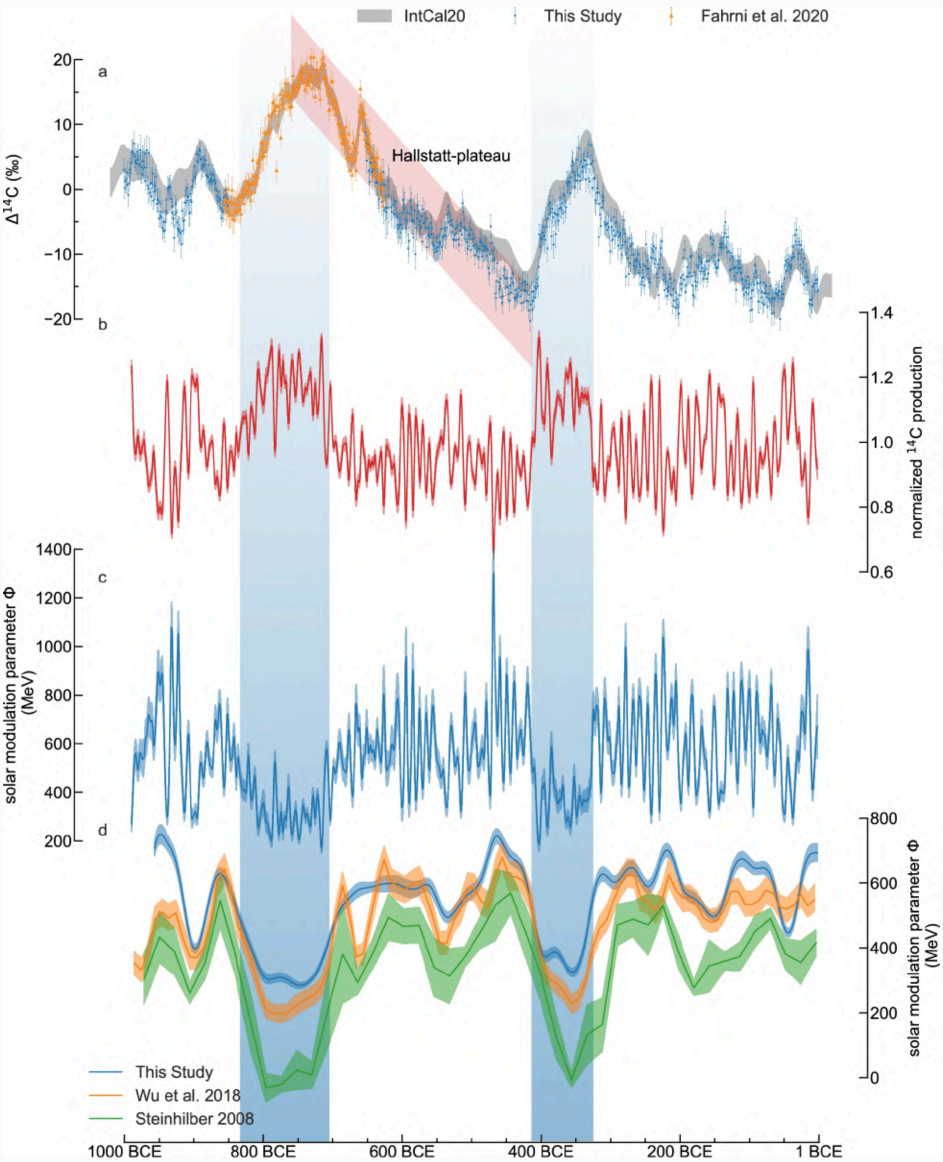

Google Earth view of the DCS path of 113 km running from Nanshan to Gaoyazi in China.

# Tree rings unlock the sun's age old secrets

Brehm, N., Pearson, C.L., Christl, M. et al. Nat Commun 16, 406 (2025)

Contributed by **Chitradeep Saha (CESSI, IISER Kolkata)**

The oldest telescopic observation of the sun is only four centuries old. Thanks to nature's silent archivists, it is possible to unveil how this star behaved multiple millennia ago. Tree rings are one such natural reservoir that keeps a record of the time. Cosmogenic isotope contents in old tree rings carry imprints of the terrestrial climate, which in turn is modulated by the sun's magnetic activity. A more magnetically active sun sweeps away galactic cosmic rays more vigorously. As a consequence, the production rate of radioactive isotopes in the earth's atmosphere goes down. This results in a reduced amount of Carbon-14 deposition in the tree rings during the period of enhanced solar activity, and vice-versa. Recently, scientists have used precise dendrochronological techniques to retrieve the sun's magnetic behaviour during the first millennium BCE with an unprecedented resolution of annual time scale. They have successfully detected a strong decennial timescale signal in the isotope data, as expected from current understanding of the solar cycles. Besides, their analysis hints towards possible occurrences of two solar grand minimum episodes during this period. Solar grand minima are phases of prolonged magnetic quiescence on the sun. These findings have implications for a better understanding of solar-stellar magnetism.




A plot showing the variation of Carbon 14 production rate (top two panels), and solar modulation potential – a measure of solar magnetic activity (bottom two panels) during 1000-1 BCE. Vertical shaded regions depict the two solar grand minima events. Notably, Carbon 14 production goes up during the reduced solar activity phases, and vice-versa.

# How does Antarctic sea ice and circulation change fate of global $CO_2$ levels

R. Ferrari,M.F. Jansen,J.F. Adkins,A. Burke,A.L. Stewart,& A.F. Thompson, Antarctic sea ice control on ocean circulation in present and glacial climates, Proc. Natl. Acad. Sci. U.S.A. 111 (24) 8753-8758 (2014)

Contributed by **Madhura Narayan Joshi (22MS, IISER Kolkata)**

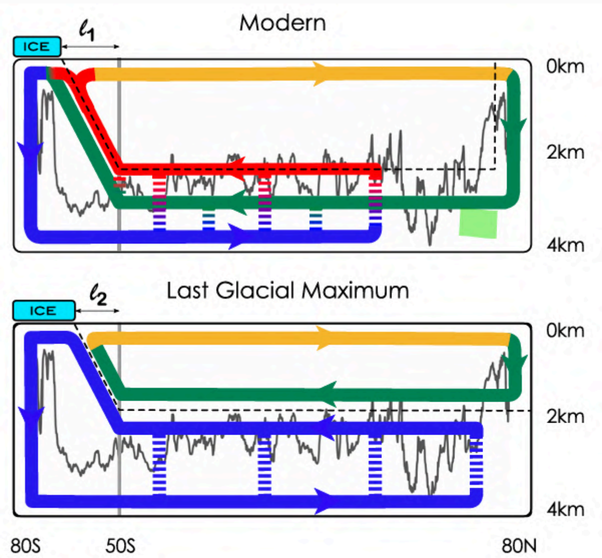
One of the key indicators of climate change is global warming — often discussed in academic circles and increasingly felt in daily life. A major driver of this warming is the rising concentration of atmospheric $CO_2$ over recent decades. Oceans, which store about 90% of Earth's carbon (combined oceanic, atmospheric, and terrestrial), play a vital role in regulating the carbon cycle and influencing climate.

During the Last Glacial Maximum (LGM), around 25,000 to 20,000 years ago, Earth's surface was 3–6 °C colder, atmospheric $CO_2$ levels were 80–90 ppm lower, and vast ice sheets and sea ice covered the poles. Unlike the modern ocean, where Arctic-origin waters dominate and Antarctic waters occupy depths below 4 km, LGM oceans were filled with Antarctic-sourced waters up to 2 km, compressing northern water masses into shallower layers. This reorganization of deep water circulation reduced $CO_2$ escape from the ocean surface and drew down atmospheric concentrations by 10–20 ppm.

Previously, these shifts were seen as a sum of individual physical changes — altered currents, increased layering, and less $CO_2$ outgassing from the Southern Ocean. Several mechanisms contributed: an equatorward shift of the Southern Hemisphere westerlies weakened upwelling of deeper water, increased stratification acted like a lid on carbon venting, expanded sea ice reduced air-sea exchange, and reduced mixing between northern and southern waters limited carbon leakage.

Overturning circulation is a large-scale movement of ocean water where warmer, lighter surface waters move toward the poles, cool, and sink to form deep currents that eventually return to the surface. This circulation is driven by two main factors: flow along isopycnals (surfaces of equal density) and surface buoyancy flux — which reflects whether water in a region is becoming lighter (due to warming or precipitation) or denser (due to cooling, brine rejection, or evaporation). These isopycnals slope steeply at high latitudes, and a key one the 27.9 kg/m³ isopycnal which separates the shallow and deep overturning branches in the Southern Ocean.

In today's climate, the sea ice edge stays close to Antarctica, and the isopycnal plunges below 2 km before reaching ocean basins There, it intersects topography like ridges and seamounts enhancing mixing and connecting the two branches into a single, figure-eight-like circulation. However, during the LGM the summer sea ice line shifted northward by about 500 km. The isopycnal followed, shoaling above 2 km and avoiding major topography. Without significant mixing, the circulation split into two separate loops: deep Antarctic waters recirculated beneath the ice, while northern-sourced waters looped above This vertical separation helped trap carbon in the deep ocean.




Schematic of overturning circulation in modern(upper) and LGM(lower) highlighting change through time. The blue ribbon is indicative of Antarctic bottom water, green indicate North Atlantic deep water, red indicates Indian and Pacific ocean deep waters and orange indicates Antarctic intermediate waters. The black dashed line is an isopycnal which separates two branches of circulation in Southern Ocean. ℓ1 is the distance between the northernmost latitude reached by the ACC, indicated by a solid gray line, and the quasi-permanent sea ice line. The ragged gray line is the crest of the main bathymetric features of the Pacific and Indian ocean basins: mixing is enhanced below this line. The extent of the quasi-permanent sea ice line has shifted equatorward compared with modern climate ðℓ2 < ℓ1Þ. Mixing-driven upwelling of abyssal waters is confined below 2 km and it cannot lift waters high enough to upwell north of the ice line. As a result the abyssal overturning circulation closes on itself, leaving above a small overturning cell of North Atlantic waters.

# Old carbon routed from land to the atmosphere by global river systems

Dean, J.F., Coxon, G., Zheng, Y. et al. Old carbon routed from land to the atmosphere by global river systems Nature 642, 105–111 (2025)

Contributed by **Swarnendu Saha (Department of Physical Sciences, IISER Kolkata)**

We usually think of rivers as part of the modern carbon cycle — transporting carbon that plants have recently absorbed from the atmosphere. But this new study reveals that rivers also act as a hidden highway, carrying very old carbon — hundreds to thousands of years old — from land into the air.

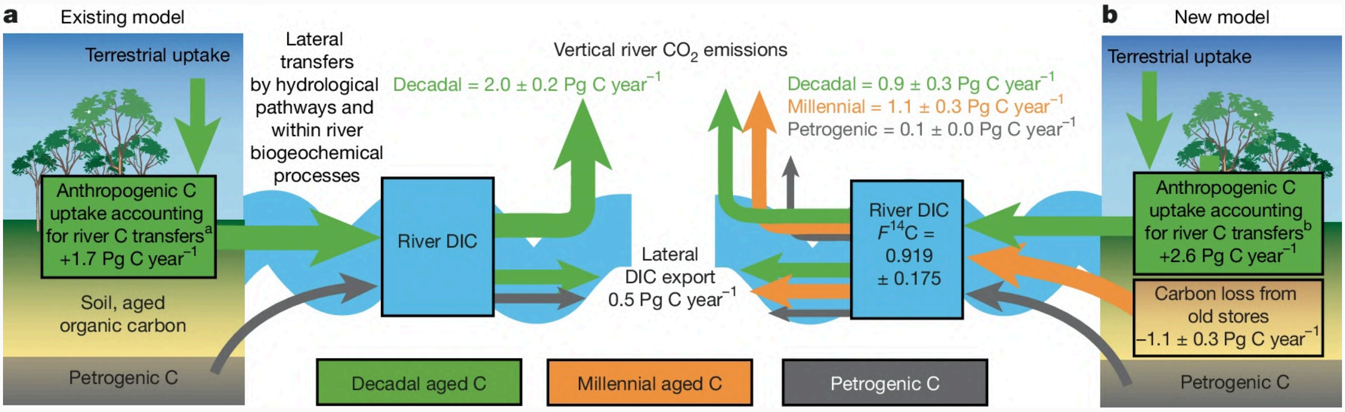
Scientists examined over 1,100 samples from rivers all over the world, looking at the type of carbon gases ($CO_2$ and $CH_4$) being released into the air. By measuring radiocarbon (a kind of natural carbon dating), they could determine how "old" the carbon was. Surprisingly, nearly 60% of river $CO_2$ emissions were found to come from millennia-old carbon, not recent plant activity.

This "old" carbon comes from deep in the soil, sediments, and even from ancient rocks. Rain and groundwater erode and carry this carbon into rivers, which then release it into the atmosphere. The amount of old carbon released — around 1.2 billion tons per year — is nearly as much as all the carbon plants worldwide absorb from the atmosphere in a year.

Different factors affect how much old carbon a river releases Rivers in areas with sedimentary rocks, like limestone, or those in high mountain regions, were more likely to release older carbon. Large rivers also showed older carbon emissions, which challenges the common belief that only small rivers are affected by old carbon sources.

These findings mean that current climate models and carbon budgets may be underestimating how much ancient carbon is being released. Old carbon, once locked in the earth, is now entering the modern carbon cycle — potentially speeding up climate change.

This study suggests we need to rethink how rivers fit into the global carbon puzzle. Rivers are not just channels for young fresh carbon. They are also leaks for ancient carbon stores, and this has major implications for how we understand and manage Earth's carbon balance.




**a) In the earlier model, it was believed that river carbon dioxide ($CO_2$) was mainly released from young, fast-cycling carbon — recently captured by plants (referred to as decadal-aged, shown in green). A smaller portion was considered to come from rocks (petrogenic carbon, shown in grey). Based on this understanding, it was estimated that about 1.7 billion tons of human-caused $CO_2$ per year was being absorbed and stored in forests and soils. b) In the revised model, new measurements of carbon age in rivers (using radiocarbon data) revealed that much of the $CO_2$ released by rivers is from older sources — carbon stored for thousands of years. This old carbon is believed to be released from deeper soils and weathered rocks. As a result, it is now recognized that rivers act as a pathway through which ancient carbon is lost from the land to the atmosphere. This finding requires a change in how Earth's carbon storage is understood and how human $CO_2$ emissions are tracked.**


# Science Games

**Questions drawn from ideas of general science.**
Science Quiz

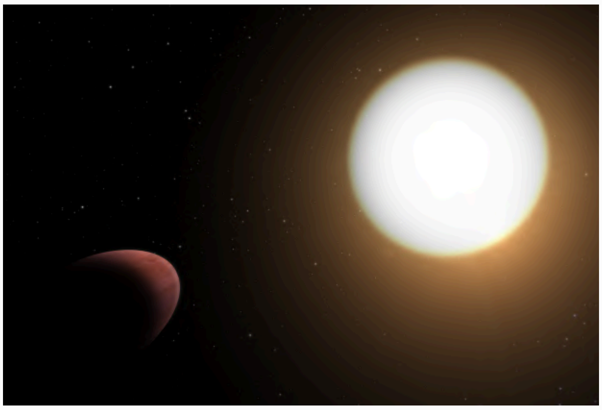
**The theme for this issue is Chemistry.**
Themed Crossword

**Link each term with the next, and complete the science word chain!**
Linked List

# General Science Quiz

**Q1.** NASA's James Webb Space Telescope recently detected several unexpected molecules — including one never before observed in any planetary atmosphere — in the scorching skies of a tidally locked gas giant exoplanet. This planet is approximately 1.2 times the mass of Jupiter and completes an orbit around its star every 30.5 hours. **Which exoplanet is it?**

I. Kepler-186f
II. WASP-121b
III. TRAPPIST-1d
IV. HD 209458b



**Q2.** This amino acid, found in certain foods and produced by the human body, has been shown in animal studies to slow signs of aging and extend lifespan when taken as a supplement. However, recent research is questioning this by examining its levels in people, monkeys, and mice across different ages. **Can you name this amino acid?**

I. Glycine
II. Taurine
III. Lysine
IV. Tryptophan

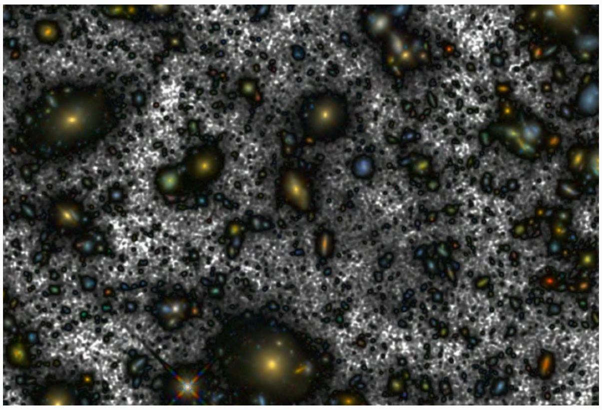
**Q3.** For years, scientists believed the mysterious dark streaks running down cliffs and crater walls on Mars were caused by flowing water. However, a recent AI-powered study published in *Nature Communications* suggests a new explanation. **What is now believed to be the more likely cause of these long, dark features that stretch for hundreds of meters down Martian slopes?**

I. Lava flows from ancient volcanoes
II. Subsurface ice melting
III. Movement of wind and dust
IV. Seepage of salty brine

**Q4.** Fossilized bones of an extinct human ancestor were recently discovered on the seafloor of the Madura Strait in Indonesia. These remains reveal a previously unknown population that hunted large animals and may have interacted culturally with other human species nearly 140,000 years ago. **Which species was this?**

I. Neanderthal (Homo neanderthalensis)
II. Denisovan
III. Homo habilis
IV. Homo erectus

**Q5.** This is one of the most iconic deep-space images ever captured, and reveals thousands of galaxies, some dating back to less than a billion years after the Big Bang. **Which space telescope took this photograph?**



I. James Webb Space Telescope
II. Spitzer Space Telescope
III. Chandra X-ray Observatory
IV. Hubble Space Telescope

**Q6.** Which hospital superbug — known for causing deadly infections — was recently discovered to survive by breaking down and consuming biodegradable medical plastics such as sutures and implants?

I. Escherichia coli
II. Staphylococcus aureus
III. Pseudomonas aeruginosa
IV. Clostridium difficile

**Q7.** Jayant Vishnu Narlikar, a pioneering Indian astrophysicist, collaborated with a prominent British cosmologist to develop a theory that challenged the conventional Big Bang model. Their theory incorporated continuous matter creation, avoided a singular beginning of time, and was based on Mach's Principle, introducing a scalar field responsible for spontaneously generating matter. **What was the name of this cosmological theory?**

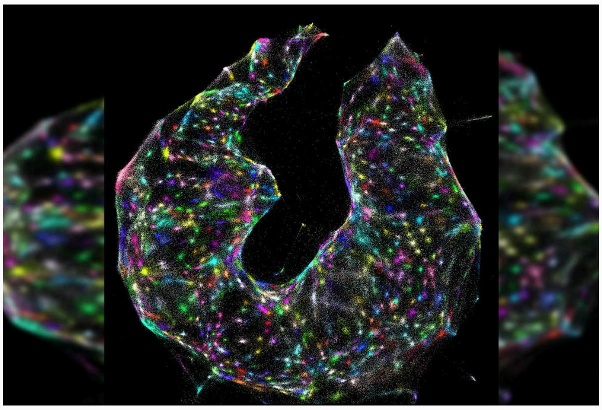
I. A model featuring inflation and quantum fluctuations that seeded cosmic structure
II. A steady-state theory with continuous matter creation via a scalar creation field
III. A universe governed only by general relativity and cold dark matter, beginning with a singularity
IV. A cyclic model involving repeated big bangs and big crunches

**Q8.** This renowned string theorist was one of the first recipients of the Breakthrough Prize in Fundamental Physics, for "opening the path to the realization that all string theories are different limits of the same underlying theory." He has made advancements in calculation of black hole entropy from first principles. **What's his name?**

I. Stephen Hawking
II. Ashoke Sen
III. Juan Maldacena
IV. Edward Witten

**Q9.** The image shows a revolutionary genetic imaging technique that maps DNA and RNA distribution inside living cells with unprecedented detail. themselves, it does not use traditional optics or lenses, instead reconstructing spatial information from genetic sequences alone. **What is this technique called?**

I. Cryo-electron microscopy
II. Fluorescence in situ hybridization (FISH)
III. DNA microscopy
IV. Optical coherence tomography



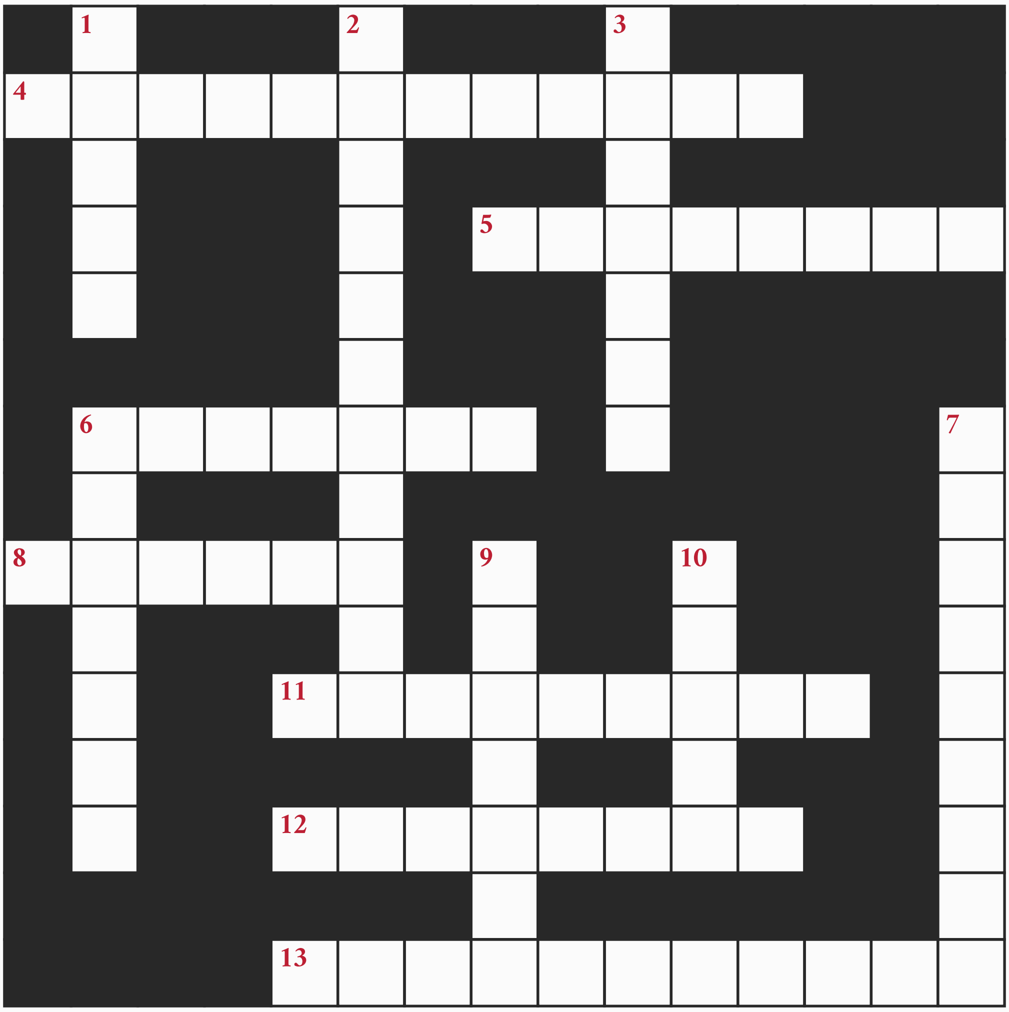
**Q10.** The surreal landscape in the image is marked by vivid green, yellow, and orange colors, caused by acidic, mineral-rich brine bubbling from hydrothermal pools. Despite their colorful appearance, some of these pools are completely devoid of life, making them among the harshest environments on Earth. **Which location is this?**

I. Yellowstone Caldera, USA
II. Danakil Depression, Eritrea
III. Mount Erebus, Antarctica
IV. Dallol, Northern Ethiopia

*Answers can be found at the end of the issue. For an interactive version of the quiz, check out our* ***website***

# Themed Crossword

This issue's crossword is drawn from **chemistry**.



## Across

4. Using electricity to split compounds into elements or simpler compounds (12)
5. Speeds up a chemical reaction without being consumed, crucial in oil refining (8)
6. Pioneer in quantum chemistry and molecular biology; explained nature of chemical bonding, won Chemistry and Peace Nobel Prizes (7)
8. Ionized, high-energy state of matter with free electrons (6)
11. Created the first widely accepted periodic table by organizing elements by atomic mass, predicted new elements (9)
12. Breaking large hydrocarbons into smaller ones (e.g., in fuel refining) (8)
13. Transition from a solid to a gas without becoming a liquid, like dry ice into vapor (11)

## Down

1. Mixture of metals and/or non-metals to create materials with improved properties (5)
2. A solid that forms and separates from a liquid during a chemical reaction; often seen in cloudiness or as solids in test tubes (11)
3. Atoms of same element with different neutron numbers; used in radiology or carbon dating (7)
6. Large molecules of repeating units, like in plastics or DNA (7)
7. Process by which particles spread out from high concentration to low concentration (9)
9. Highly reactive molecule or atom with an unpaired electron (7)
10. Trade name for refrigerant gases; damaging to the ozone layer (5)

*Solution can be found at the end of the issue. For an interactive version of the crossword, check out our* ***website****.*

# Linked List

Linked List is a general science-based word game. The rules are straightforward:
1. The goal is to guess eleven words that have been drawn from science.
2. The first word (the seed) will be provided to you, and hints and number of letters will be provided for the remaining words.
3. You are also informed that the first letter of any word is the last letter of the previous word. So the first letter of the second word will be the last letter of the seed word, the first letter of the third word is the last letter of the second word, and so on.
4. This property goes all the way, so that the last letter of the last (eleventh) word is also the first letter of the seed word.

Find all the words!

Today's seed: **TURBULENCE**

1. A community of organisms interacting with their environment through energy flow and nutrient cycling. (9)

| E | | | | | | | | |
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2. All chemical reactions in an organism that produce energy from food and build or break down molecules. (10)

| | | | | | | | | | |
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3. A permanent change in DNA sequence that can alter traits or cause genetic disorders. (8)

| | | | | | | | |
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4. The kidney's functional unit that filters blood, reabsorbs useful substances and forms urine. (7)

| | | | | | | |
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5. A DNA/RNA building block made of a sugar, phosphate group and nitrogen base. (10)

| | | | | | | | | | |
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6. The physical process of water changing into vapor, often driven by heat, as part of the water cycle. (11)

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7. A nearly massless, chargeless particle from nuclear reactions that rarely interacts with matter. (8)

| | | | | | | | |
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8. The gravitational path followed by a celestial body around another object. (5)

| | | | | |
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9. Related to movement of Earth's lithospheric plates, causing quakes and mountain formation. (8)

| | | | | | | | |
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10. A substance that speeds up a chemical reaction without being consumed. (8)

| | | | | | | | T |
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*Solution can be found at the end of the issue. For an interactive version of this game, check out our* ***website****.*

# Join the Conversation

## Contribute

Contributions are welcome from students and faculty members across all academic institutions, on a rolling basis. Submission portals for all types of content can be found on our website. More detailed guidelines are also available there, so please refer to the linked page if you're interested in contributing. For any queries, feel free to contact us at *scicomm@iiserkol.ac.in*.

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We publish engaging articles on scientific ideas, provided they are accessible to a broad audience and not limited to experts. Submit your articles **here**.

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We feature science-themed games such as crosswords, quizzes, and word-link challenges. If you have content for these or ideas for new games, please email us at *scicomm@iiserkol.ac.in*.

**Short Summaries**

To showcase cutting-edge research, we publish short summaries (350–400 words) of recently published scientific papers. The summary should broadly outline the research questions and highlight the key findings.. Submit your research stories **here**.

**Interview Recommendations**

If you would like us to interview a particular scientific personality, or if you have an interview you'd like us to consider for publication, please reach out to us at *scicomm@iiserkol.ac.in*.

More importantly, we would love to hear any feedback that you might have about this endeavour, so please send us your comments at *scicomm@iiserkol.ac.in*.

## Join our team

We are currently looking to expand our team. If you are interested in what we do and are confident that you will be able to devote time to this, please reach out to us at *scicomm@iiserkol.ac.in*. We will be happy to discuss possible roles for you depending on your skills.

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Sayan Saha

**Science Games**

Alekhya Kundu

# The Last Page

## Crossword

**Across**

4. ELECTROLYSIS
5. CATALYST
6. PAULING
8. PLASMA
11. MENDELEEV
12. CRACKING
13. SUBLIMATION

**Down**

1. ALLOY
2. PRECIPITATE
3. ISOTOPE
6. POLYMER
7. DIFFUSION
9. RADICAL
10. FREON

## Quiz

1. WASP-121b
2. Taurine
3. Movement of wind and dust
4. Homo erectus
5. Hubble Space Telescope
6. Pseudomonas aeruginosa
7. A steady-state theory with continuous matter creation via a scalar creation field
8. Ashoke Sen
9. DNA microscopy
10. Dallol, Northern Ethiopia

## Linked List

1. ECOSYSTEM
2. METABOLISM
3. MUTATION
4. NEPHRON
5. NUCLEOTIDE
6. EVAPORATION
7. NEUTRINO
8. ORBIT
9. TECTONIC
10. CATALYST

**You made it to the end! While we cook up the next issue, here's a random photo dump.**

*Tradition and Modernity*: A Dazzling Fusion of Culture and Creativity - IISER Kolkata's Fashion Show Celebrates Bold Expression and Timeless Aesthetics. *Credit: Jibitesh Das*

On the occasion the *20th Institute Foundation Day* and the Open House event with science exhibition organized was attended by more than 1000 students from neighbouring schools with lots of excitement. *Credit: IISER Kolkata*

*The Prisoner of Conscience* - A still from the IICM 2024 stage act. *Credit: Swarnendu*