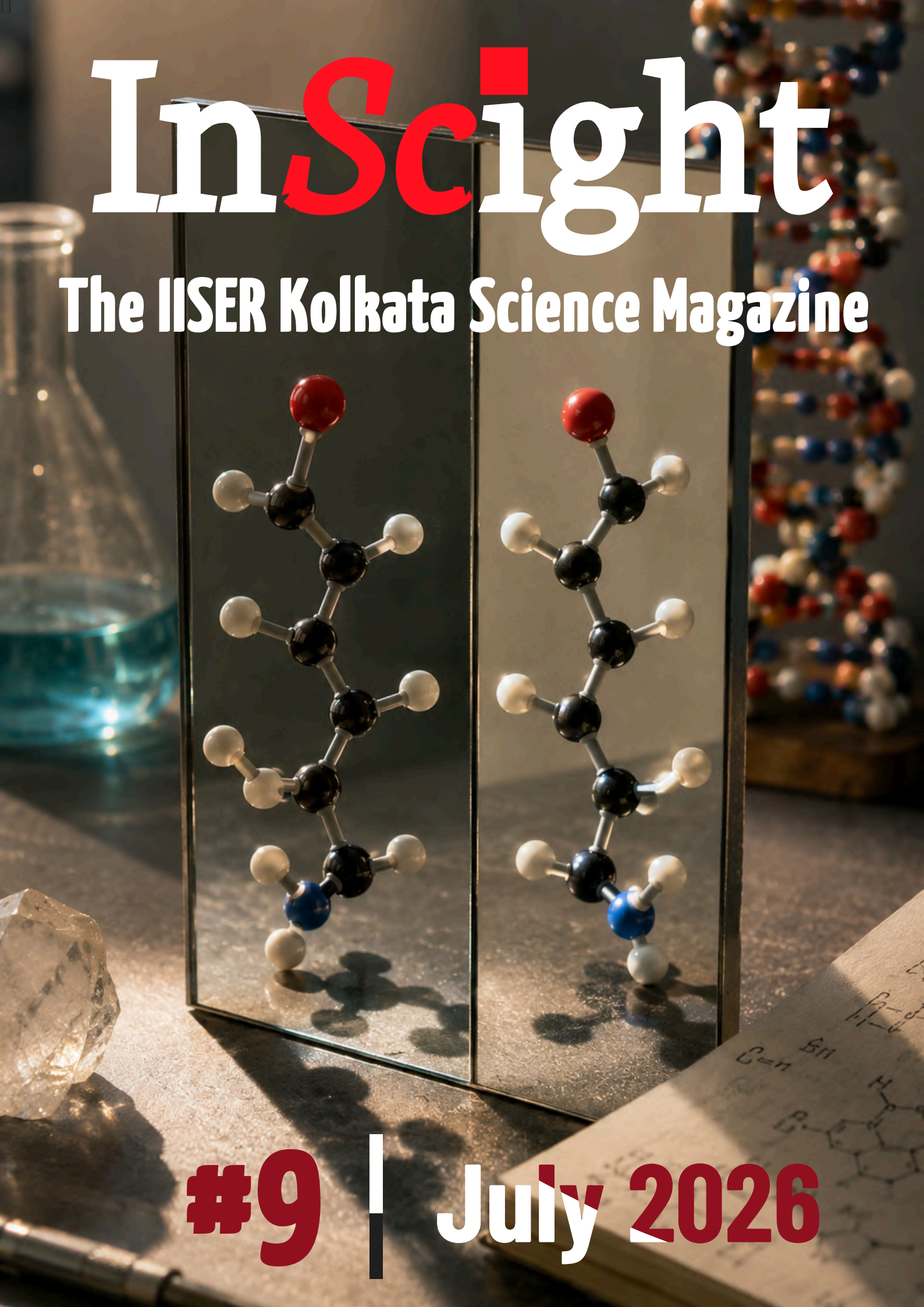


InSight

The IISER Kolkata Science Magazine

#9 | July 2026

Tradition, Science, and the Search for Truth

*Foreword by **Prof. Sayam Sen Gupta***
Department Of Chemical Sciences, IISER Kolkata

First, my warmest congratulations to the team behind *InScight*. Running a scientific magazine is an experiment in itself - one that demands curiosity, persistence, and no small measure of courage. At a time when most information reaches us through fleeting WhatsApp forwards and endless social media reels, it is deeply heartening to see students choosing the slower, more thoughtful medium of print. There is a unique joy in telling the stories behind scientific discoveries, and *InScight* gives those stories a home. For that, our entire community owes its editors and contributors sincere gratitude.

When the editorial team invited me to write this piece, I found myself wondering what message would best suit the first issue. One question that repeatedly surfaces today is whether science and tradition stand in opposition. It is a fascinating debate, and one that deserves a closer look.

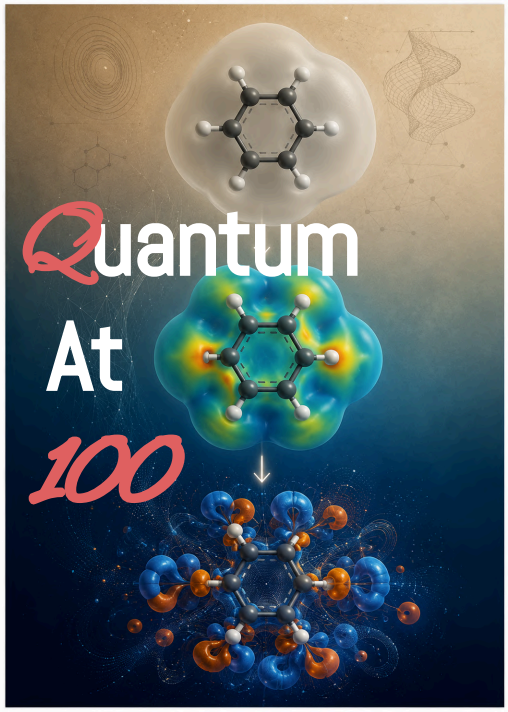
Consider the story of beriberi, a disease that once devastated communities across Asia after steam mills began polishing rice, removing its nutrient-rich outer layers. Long before Christiaan Eijkman demonstrated the role of thiamine through careful experiments in the late nineteenth century, many South Asian communities had already developed the practice of parboiling paddy before milling. This simple process-still familiar to us as "seddho chaal" in Bengal and in the preparation of rice for foods such as idli and dosa - preserved much of the vitamin within the grain. The same pattern appears elsewhere. After screening more than 240,000 compounds without success, Chinese scientist Tu Youyou turned to traditional Chinese medical texts for inspiration that were used for over two millennia to treat fevers. Her team identified sweet wormwood (Artemisia annua) as a treatment for intermittent fevers and, in 1971, isolated artemisinin, its potent antimalarial compound. Artemisinin-based therapies are now the WHO's standard treatment for malaria, and Tu Youyou received the 2015 Nobel Prize in Medicine.

None of these communities for centuries knew about thiamine, or artemisinin. What they possessed was something equally valuable: knowledge accumulated through generations of observation, experimentation, and lived experience. Tradition, in this sense, is not superstition. It is a repository of successful solutions refined over centuries. But tradition has one limitation - it evolves slowly. When the Industrial Revolution transformed food production and populations grew rapidly, longstanding practices could not adapt quickly enough. This was not a failure of tradition; it was a mismatch of timescales.

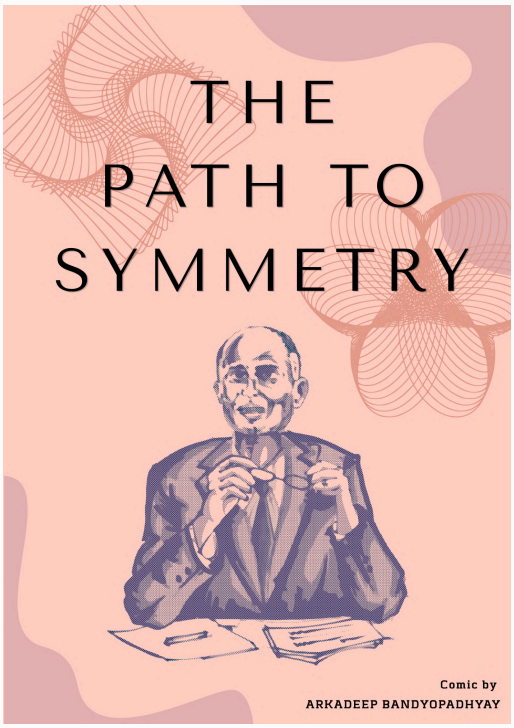
That is where hypothesis-driven science becomes indispensable - not as a replacement for tradition, but as its accelerant. What once required centuries of trial and error can now be understood within a generation through careful experimentation, mechanistic insight, and peer review. The COVID-19 pandemic offered perhaps the clearest demonstration. Within weeks of the first reported cases, scientists had identified the virus and sequenced its genome. Within months, they had determined the structure of its spike protein. Within about a year, that knowledge had culminated in safe and effective vaccines developed at an unprecedented speed.

Knowledge accumulated slowly across generations and knowledge built rapidly through scientific inquiry are not competing ways of understanding the world. They are complementary. One reminds us where wisdom comes from; the other shows us how quickly that wisdom can grow when guided by evidence.

May *InScight* continue to tell both kinds of stories.



What if the electron never truly orbited the nucleus, not because its path was too small to be... Read the rest here.



The Path To Symmetry: A Comic by Arkadeep Bandyopadhyay... Read the rest here.

A Word from the Editors

Debanuj Chatterjee
Editor at InScight, *IISER Kolkata*

Every scientific breakthrough begins with a question. Some questions seek to understand the universe at its most fundamental level, while others emerge from observing the natural world around us or reflecting on the journeys that shape scientific careers. Despite their diversity, they are united by a common thread: curiosity. It is this curiosity that continues to drive science forward, and manifests as the anthem of InScight.

We begin at the fascinating intersection of theoretical physics and mathematics: the world of conformal bootstraps. A remarkable blend of physics, geometry, and mathematical consistency forms the foundation of this field. The journey explores how quantum mechanics can be demystified by demanding the self-consistency of nature.

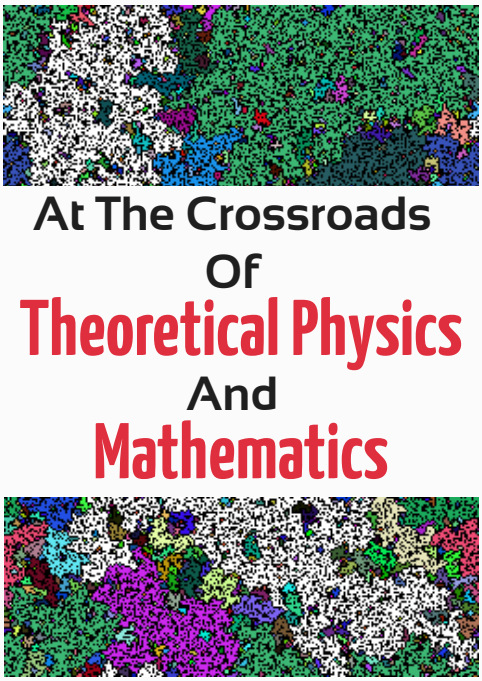
Gears change as we delve into the world of chemistry. Our next article explores the development of asymmetric synthesis and modern hybrid catalytic systems. The ability to selectively produce one molecular form over another has been transforming pharmaceutical science and chemical engineering over the years. This underscores how these discoveries are fundamentally reshaping modern medicine.

This year marks one hundred years since Werner Heisenberg's formulation of matrix mechanics, a milestone that forever changed our understanding of reality. Our feature on "Quantum at 100" revisits the revolutionary ideas that gave birth to quantum mechanics and reflects on how they continue to influence modern science, ranging from condensed matter physics to quantum information theory to materials science.

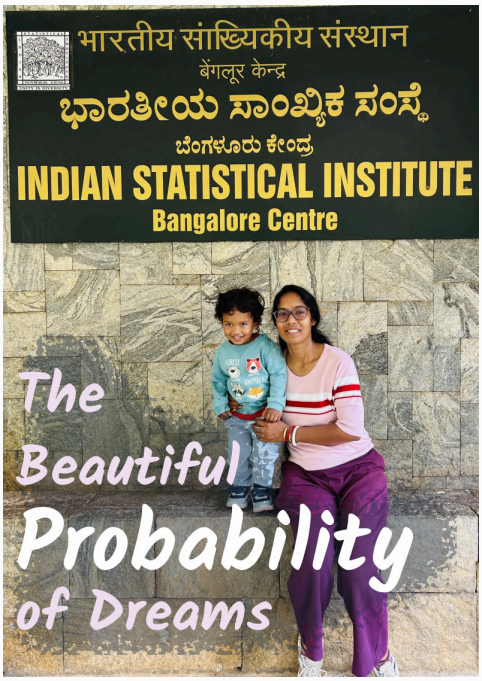
Science, however, is not confined to laboratories or equations alone. In a deeply personal narrative, we follow the journey of a young scientist whose dream of studying at IISER Berhampur unfolded through uncertainty, perseverance, and probability itself. It is a reminder that every scientific career is built not only on intellect, but also on resilience and the courage to embrace the unknown.

We also travel millions of years into the Earth's past to uncover the mystery behind the disappearance of giant dragonflies. Their story offers a fascinating glimpse into how changes in atmospheric composition and planetary environments have shaped the evolution of life on Earth.

Whether you are a student, researcher, or simply a curious reader, we hope this issue will spark new ideas and conversations. As we stand at a crucial crossroads of Indian science and education, we hope the growing InScight community continues to champion scientific thinking. The future of science depends not only on discoveries in laboratories but also on a society willing to ask questions. Afterall every scientific breakthrough begins with a question.

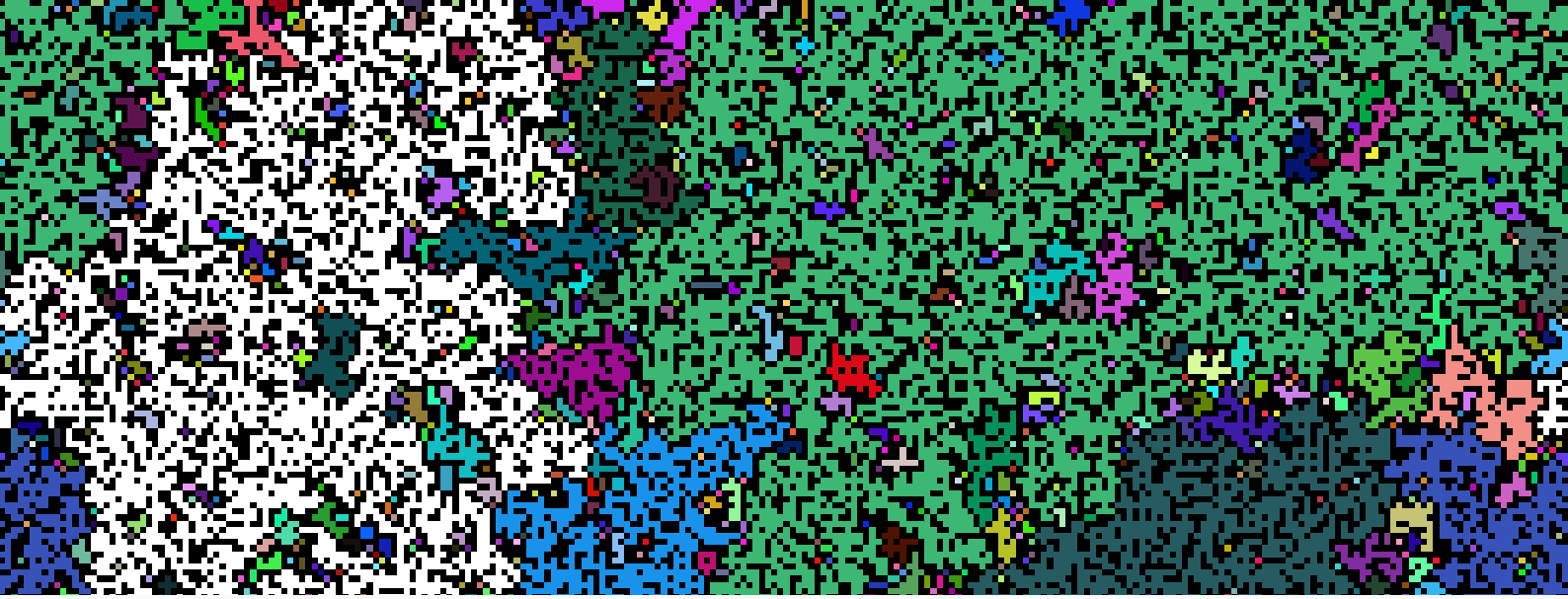


What if we do not have to look for solutions to equations of motion abiding physical laws, rather the solutions are forced upon us, leaving almost no room of choice? This article explores how simple consistency rules, pushed to their limits through a mathematical machinery called conformal bootstra..... Read the rest here.

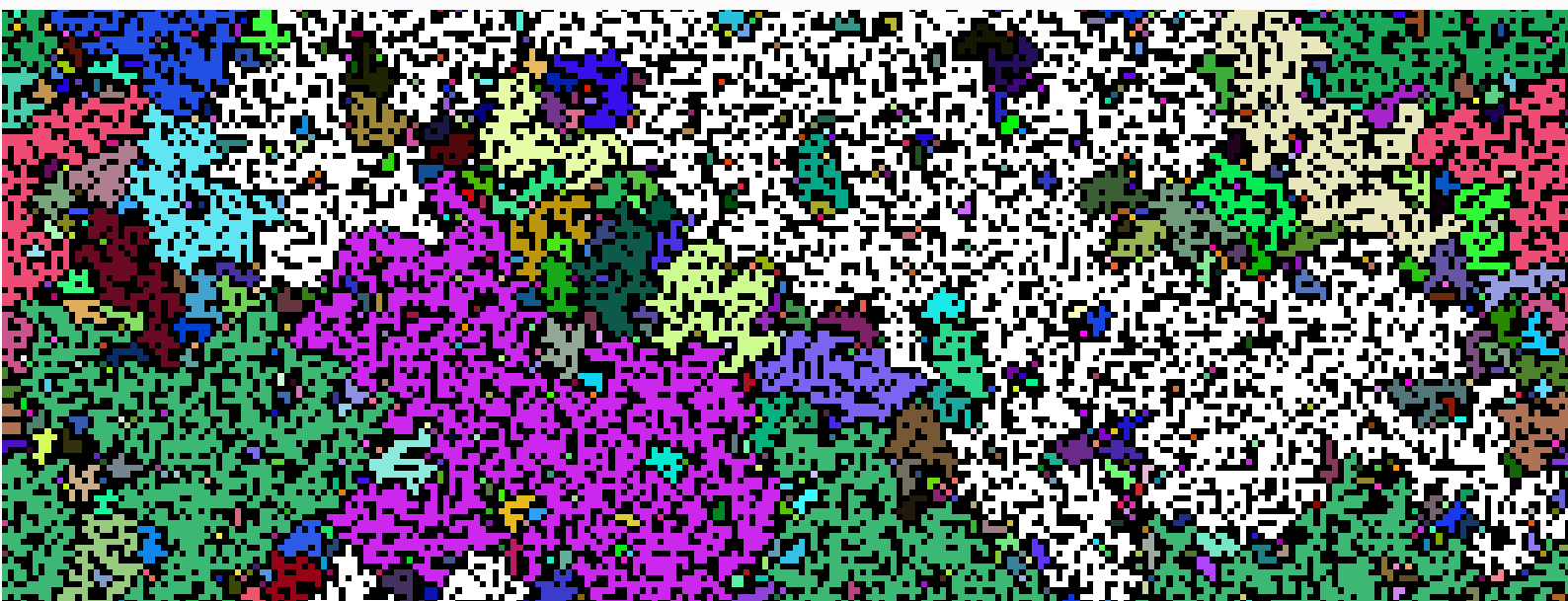


Growing up as a girl in a rural village, I never imagined I would end up where I am today. Now, as an Assistant Professor of Mathematics at IISER Berhampur, I look back and realise how simple the recipe for success truly is. My journey taught me that you can overcome almost any obstacle if you stay ..... Read the rest here.

In This Issue



At The Crossroads Of Theoretical Physics And Mathematics



At the Crossroads of Theoretical Physics and Mathematics

Sridip Pal *Junior Professor in Theoretical Physics, The Institut des Hautes Études Scientifiques, Paris*

Jan 02, 2026

Reviewed By: Suman Halder

What if we do not have to look for solutions to equations of motion abiding physical laws, rather the solutions are forced upon us, leaving almost no room of choice? This article explores how simple consistency rules, pushed to their limits through a mathematical machinery called conformal bootstrap, can pin down entire quantum worlds and reveal hidden order in everything from critical phases of matter to the geometry of space-time itself.

Sridip Pal works on the conformal bootstrap, a non-perturbative framework for uncovering universal structures in conformal field theories, with applications to quantum gravity, quantum chaos, and hyperbolic geometry. He was trained at IISER Kolkata, earned his doctorate at the University of California in San Diego, and subsequently held a position as a Founder's Circle Member at the Institute for Advanced Study in Princeton.

Physics often gives the impression of endless freedom. We write down equations, introduce parameters, and imagine a vast landscape of possible theories. Yet again and again, that freedom turns out to be illusory. Beneath the complexity, nature seems to obey a quiet discipline—an insistence that everything must fit together without contradiction. Much of my research has been driven by a simple question: *how far does that insistence go?*

That question led me early on to *conformal field theory*, or CFT.

CFTs appear most naturally at *continuous phase transitions*—moments when a system is delicately poised between two different states, and small changes can have effects on all length scales at once. A familiar example is a magnet that is just about to lose its magnetization as it is heated: tiny fluctuations in one region can influence behavior far away. Another intuitive picture comes from connectivity. Imagine gradually adding links to a large network. At a certain threshold, disconnected clusters suddenly merge into a system-spanning structure. Right at that threshold, patterns exist on all scales, and no single length scale dominates.

A useful way to picture this is to imagine zooming in on the system again and again. No matter how much you magnify the image, new structure keeps appearing, and the patterns you see look much the same at every scale (see this YouTube video about renormalization group flow in Ising model). It is precisely in these scale-free situations that conformal symmetry emerges, making CFTs powerful universal descriptions of otherwise very different physical systems. These same ideas later turn out to play a central role in modern approaches to quantum gravity as well.

A conformal field theory is built from *local operators*—mathematical objects that represent physical quantities measured at specific points, such as the spin of an atom in a magnet. The basic observables of the theory are their *correlation functions*, which describe how measurements at different points influence one another. Remarkably, conformal symmetry fixes the form of these correlation functions almost completely. What remains undetermined is a collection of numerical constants.

Once this set of numbers is known, every correlation function in the theory can, in principle, be reconstructed. In this sense, these numbers uniquely specify the theory itself. We refer to them collectively as the *CFT data*.

This immediately raises a natural and surprisingly subtle question:

Can an arbitrary choice of numbers define a physically consistent theory?

The answer is no. Not every collection of numbers is allowed. For a theory to make physical sense, its CFT data must satisfy a large web of consistency conditions. These conditions reflect basic physical principles: energy must be conserved, information cannot travel faster than light, probabilities must always add up to one, and different ways of describing the same physical process must agree with one another. In technical language, these requirements are encoded in constraints such as *symmetry*, *unitarity*, *crossing symmetry*, and *modular invariance*. Together, they impose remarkably strong restrictions on what the CFT data can be—and it is precisely these restrictions that lie at the heart of the **conformal bootstrap**: once basic principles such as

symmetry, locality, and unitarity are imposed, the theory seems to leave remarkably little room to maneuver.

The *conformal bootstrap* is a framework that makes this rigidity visible. Rather than starting from a microscopic model or equation of motion, the bootstrap asks a more austere question: *what must be true of any theory that is consistent?* The resulting constraints often prove far stronger than intuition would suggest.

Historically, the conformal bootstrap is not a new idea. Its roots go back to the work of Alexander Polyakov in the early 1970s, who emphasised that consistency conditions such as crossing symmetry should be powerful enough to determine a theory on their own. For many years, this viewpoint remained more philosophical than practical. It was only much later—most notably through work by Rattazi, Rychkov, Tonni, Vichi in the late 2000s—that the bootstrap was revived in a concrete and systematic form, with new analytical and numerical tools that made Polyakov's original vision operational. A nice historical account can be found in this recent article by Slava Rychkov.

A helpful way to think about the conformal bootstrap is through the analogy of *Sudoku* (see figure. 1). In a Sudoku puzzle, only a few numbers are filled in at the start, while the rest of the grid is left blank. The rules are simple: each row, column, and subgrid must contain every digit exactly once. Yet these rules are enforced *everywhere* at once.

A choice made in one corner of the grid can quietly constrain entries far away, and in a well-posed puzzle, the solution may be essentially unique.

The conformal bootstrap works in much the same way. The unknown entries are the basic numerical data of a conformal field theory—such as the dimensions of operators and how strongly they interact—while the rules come from fundamental physical principles like symmetry, unitarity, and consistency under crossing. These rules must be satisfied simultaneously, across all possible ways of probing the theory. As a result, the allowed data are often far more restricted than one would naively expect.

In practice, this logic is made concrete in two complementary ways. *Numerical bootstrap* methods systematically scan the space of possible data and discard anything that violates the rules. What remains are small "islands" of consistency—regions where all constraints may possibly be satisfied at once (see e.g. arXiv:2311.15844[hep-th]). *Analytical bootstrap* methods, by contrast, explore the same constraints in extreme or asymptotic regimes, such as very large energies or large spin. Rather than carving out islands, they reveal universal patterns that must emerge far out in the spectrum, independent of microscopic details.

This perspective unifies numerical bootstrap methods, which carve out allowed "islands" of theories, and analytical bootstrap approaches, which focus on asymptotic regimes such as large energy or large spin. Together, they suggest a striking conclusion: conformal field theories are far more rigid than they appear.

This striking feature shaped my work during postdoctoral years: first at the Institute for Advanced Study (IAS), Princeton [2019-22], and later at California Institute of Technology (Caltech)[2022-25]. The problems evolved, but the underlying question remained the same: *when consistency is taken seriously, what is a quantum theory actually allowed to do?*

What follows is not a comprehensive account of all my work during these years. Instead, I will focus on a few problems from my time at IAS and Caltech that best illustrate how my thinking has evolved, and how ideas from consistency, symmetry, and asymptotics have guided that evolution. Many other projects unfolded in

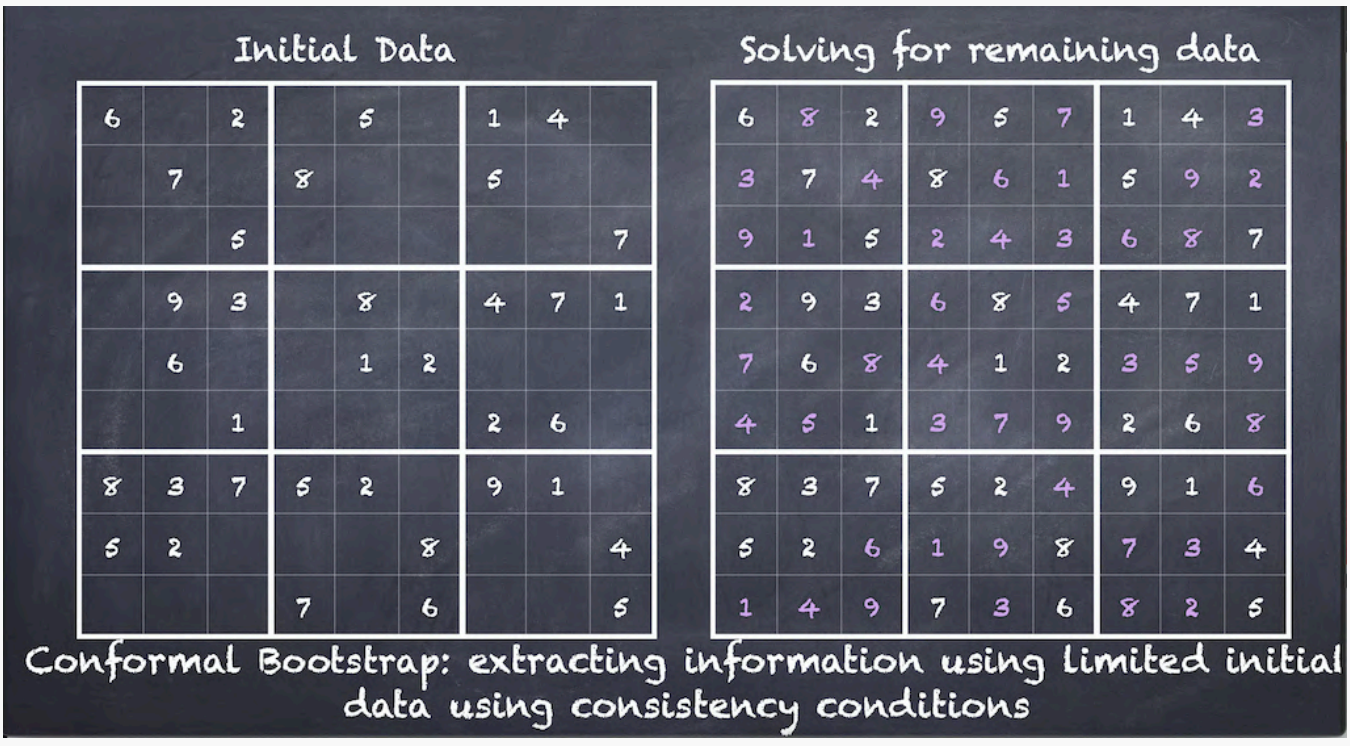


FIG 1 : *Analogy between* Sudoku *and* Conformal Bootstrap*: solving theory using consistency conditions.*

parallel, but these selected threads capture the core themes that continue to shape my research.

When Quantum States Have No Room to Spread Out

How consistency alone can dictate the structure of quantum worlds

At IAS, this question drew my attention to the high-energy structure of quantum spectra. Every quantum system comes with a spectrum—a list of allowed excitations, like the notes a musical instrument can play. A natural question is how those notes are spaced. As one moves to higher and higher energies, can there be long stretches of silence, or must the spectrum inevitably become crowded?

In two-dimensional conformal field theories, this question had been sharpened into a precise conjecture by Baur MukhametZhanov and Sasha Zhiboedov in 2019 (arXiv:1904.06359[hep-th]). They proposed that in any consistent two dimensional CFT, large gaps between states at high energies cannot persist and in fact the gap is upper bounded by 1. The conjecture was compelling, but proving it required writing down what mathematicians call a *band-limited* function with suitable properties.

I became deeply involved in tackling this problem in the last few months of my PhD at UC San Diego. What helped enormously was a set of tools I had been fascinated by since graduate school: *Tauberian theorems* (see this wikipedia page) These results relate global growth properties to fine asymptotic behavior and form one of the most elegant bridges between analysis and physics. Over the years, they had quietly shaped how I thought about spectra, and here they turned out to be exactly the right language. In fact, the original paper by Baur and Sasha was already written in this language, which made it feel immediately familiar and allowed me to understand its ideas at a very deep level.

For about a month, I experimented with different test functions, trying to find one that would capture the constraints sharply enough to close the argument. Most choices fell short in subtle ways. Eventually, one particular function did exactly what was needed: it enforced the bootstrap constraints with the right balance of rigidity and flexibility. With that crucial ingredient in place, the conjecture fell into place, and I was able to complete the proof.

Around the same time, my friend and collaborator Shouvik Ganguly [he's an electrical engineer by training, somehow I convinced him that it is an interesting math problem for him to spend time on!] suggested a different idea aimed at improving other aspects of the state-counting problem studied by Baur and Sasha. His approach attacked the problem from a complementary angle. At first glance, the two perspectives—my proof of the conjectured gap bound and Shouvik's improvements on related counting questions—seemed rather distant from one another. Yet I could not shake the feeling that they were connected at a deeper level. We wrote down our understanding in a joint paper arXiv:1905.12636 [hep-th].

Stripped to its essentials, the story raised two closely related questions. First: what is the *optimal* bound on how far apart quantum states can be spaced? Second: given a fixed energy window, how many states can fit inside it in the most efficient way? These are two sides of the same coin—one phrased in terms of gaps, the other in terms of density. From the beginning, I believed that the answers to these optimality questions could not be independent, and that a unifying picture must lie underneath, still waiting to be fully uncovered.

The final ingredient came after I moved to IAS, from analytic number theory.

Through conversations with Sergey Tikhonov, a mathematician, I was pointed toward the *Beurling–Selberg extremization problem*, a famous and classical construction originally developed to obtain optimal

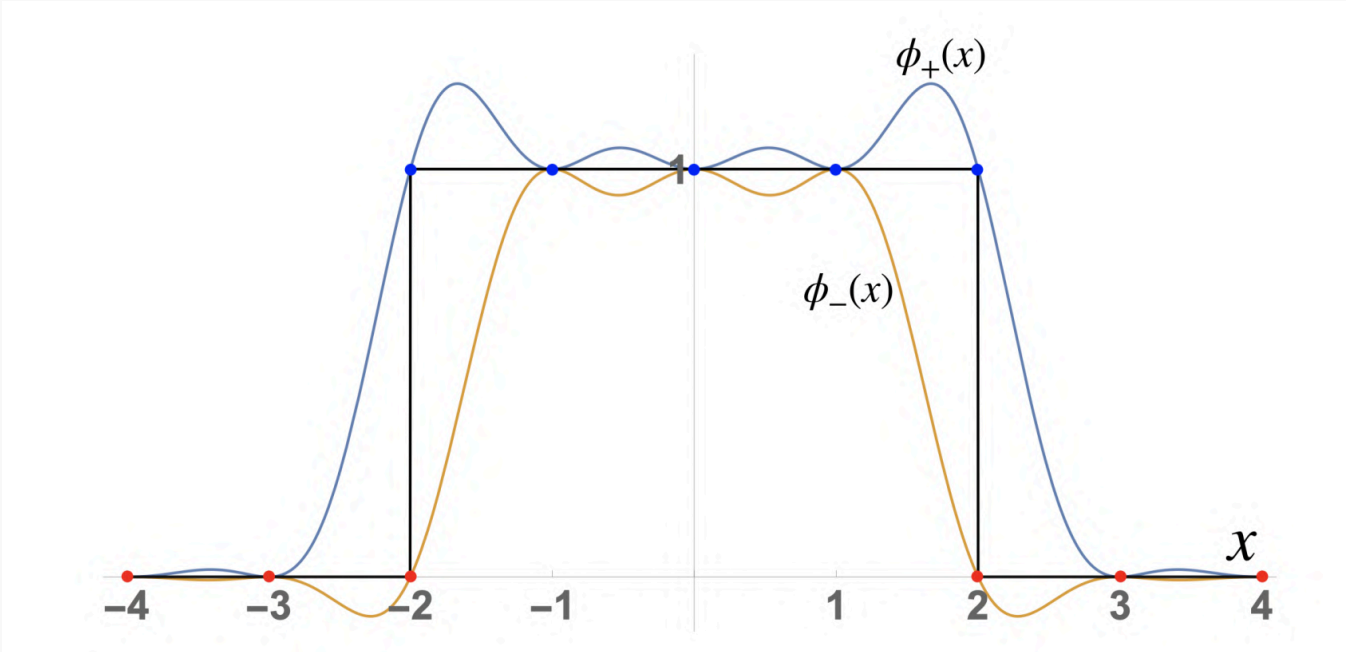


FIG 2 : *Beurling-Selberg extremal functions for integer sized bins*

bounds in analytic number theory. It is not a tool one normally expects to encounter in quantum field theory—but once the connection became clear, it was unmistakable. Beurling–Selberg extremal functions provided precisely what was needed to translate abstract bootstrap consistency conditions into sharp, quantitative bounds on operator spacing and operator counting. What made this framework especially powerful was that it allowed me to construct extremal functions in a systematic and controlled way. With this machinery in hand, two results emerged naturally. First, it yielded another proof of the conjectured optimal gap between states at high energies—this time in a form that I found aesthetically cleaner and conceptually more satisfying than my earlier approach of mine. Second, it made it possible to answer a closely related question: given a fixed energy window of half-integer size, how many states can be optimally packed into it at high energies?

Around the same time, to my great pleasure, Baur also joined the Institute for Advanced Study as a postdoctoral fellow. This made it natural to begin discussing these ideas together in detail. I invited him to join the adventure, and together we figured out how the solution to optimal counting problem could be extended beyond integer or half-integer bin sizes. Working together, we developed a unified treatment that covered arbitrary bin widths and sharpened the connection between spacing bounds and optimal state counting. Eventually, we wrote up these results in a joint paper arXiv:2003.14316[hep-th], bringing this part of the story to a satisfying close —at least for now. We established *quantum states have no room to spread out. Large gaps are forbidden. The spectrum must fill in.*

What emerged was a clear lesson: the high-energy structure of a 2D CFT is not a matter of choice. It is tightly choreographed by symmetry, consistency, and deep mathematics.

Listening to Spectra

The next direction of my IAS work began not from calculations, but from a conversation.

I had not been thinking about geometry at all when Dalimil Mazáč (another postdoctoral fellow at IAS) in winter of 2021 told me about an idea he had been considering: whether techniques inspired by the conformal bootstrap could be used to constrain the *Laplace spectrum of hyperbolic manifolds*—curved spaces with constant negative curvature. Until that moment, this direction simply was not on my radar.

But as Dalimil explained the idea, something clicked immediately. The analogy was too natural to ignore. If consistency can so powerfully constrain quantum spectra, why should the same logic not apply to the spectrum of vibrations on a curved space?

I jumped into the project with Dalimil. We soon found that this was not a superficial analogy. We could find concrete bounds for 3 dimensional manifolds. Later Petr Kravchuk, another postdoctoral fellow at IAS, joined the project and we turned our attention to 2 dimensional surfaces.

By translating bootstrap ideas into the language of hyperbolic symmetry and harmonic analysis, we derived new, rigorous bounds on Laplacian eigenvalues for broad classes of hyperbolic surfaces and orbifolds, resulting in a joint publication arXiv:2111.12716[hep-th].

In geometry, one often speaks of "hearing the shape of a drum"—the idea that the spectrum of an operator encodes deep information about the underlying space. What struck me was how naturally the bootstrap fit into this perspective: spectra, once again, were being determined by consistency alone. In many cases, our upper bounds beat the previous record holders for 40 years. in mathematics. Throughout this work, Peter Sarnak, a famous mathematician's enthusiasm about our work was a powerful source of encouragement (see his Grenoble lecture).

By the time I left IAS, a broader picture had crystallized. The bootstrap was not just a technique for CFTs. It was a way of thinking—a method for extracting order from symmetry, whether the object of study was a quantum spectrum or the shape of space itself.

With that perspective in place, I arrived at Caltech ready to sharpen these ideas and push them into new regimes.

Sharpening the Picture at Caltech: Large Spin

When I moved to Caltech, the questions I had been circling did not disappear. Instead, they became sharper. I was still interested in spectra and asymptotics, but now I wanted to understand *how* spectral crowding happens,

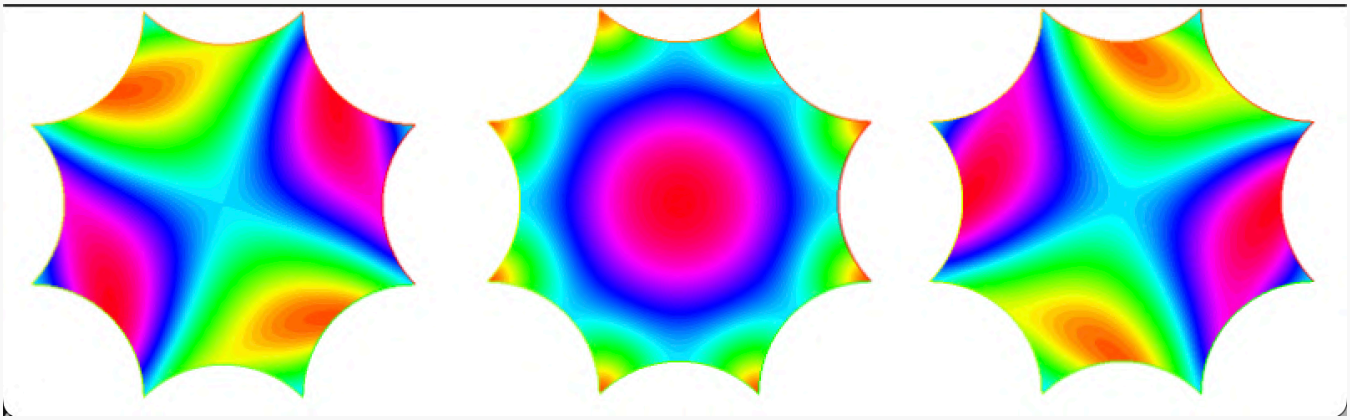


FIG 3 : *Picture taken from Wikipedia: eigenfunctions corresponding to the first three positive eigenvalues of Laplace operator on Bolza surface, the most symmetric genus 2 hyperbolic manifold.*

and what universal structures emerge when one looks closely enough. This shift led me to focus on the *large-spin* regime. Large-spin operators sit far out in the spectrum, but they are among the most constrained.

In joint work with Slava Rychkov and Jiaxin Qiao (arXiv:2212.04893), we showed that large-spin spectra exhibit striking universality. Many microscopic details wash out, leaving behind patterns dictated almost entirely by crossing symmetry and causality. Large spin acts like a microscope: by zooming far enough out, messy details blur away and clean structure comes into focus.

I returned to this theme again in later work with Jiaxin Qiao and Balt van Rees (arXiv:2505.02897), where we studied dense spectra at large spin in even greater detail.

A Different Kind of Universality: Proving the HKS Conjecture

Alongside the large-spin program, my time at Caltech also led me to a different problem—one that did not rely on large spin at all.

In 2014, Hartman, Keller, and Stoica conjectured that unitary two-dimensional CFTs exhibit a universal form of the *grand-canonical free energy* at large central charge. The conjecture was motivated by holography and black-hole physics, but a general proof had remained elusive.

In work with Jiaxin Qiao and Indranil Dey (arXiv:2410.18174), we provided such a proof using tools from the *analytical modular bootstrap*. By studying the torus partition function, we derived universal inequalities that follow solely from modular invariance and unitarity.

These inequalities allowed us to rigorously control the large-central-charge limit and show that the conjectured behavior is a necessary consequence of consistency itself.

Life Between Equations

Looking back, my postdoctoral years were shaped as much by people and places as by problems. At IAS, life and physics blended together in ways that were sometimes intense, sometimes joyful, and often unexpected. There were long afternoons of card games and late-night conversations, periods of quiet focus punctuated by dinners with friends, and stretches of uncertainty during the COVID years that made even small moments feel precious. I spent many hours walking through the woods around Princeton, where ideas had a way of loosening themselves during long, solitary walks. Later, in California, the rhythm changed—the sun, the Pacific, puzzle solving games squeezed between calculations, evenings that stretched late into the night. Conferences and travel filled the calendar, including memorable trips abroad, from intense workshops to moments of awe standing near Iguazú Falls in Brazil. Through it all, physics never felt separate from life; it was woven into it.

What I value most from this period, however, is the community that formed around me. I was fortunate to build close friendships and collaborations with an extraordinary group of people: Brato Chakrabarti, Shreya Biswas, Shouvik Ganguly, Dalimil Mazáč, Sanja Nedić, Anshul Adve, Baur Mukhametzhanov, Petr Kravchuk, Ahanjit Bhattacharya, Peter Stoffer, Serena Gradel, Andrew Kobach, Nathan Benjamin, Yuya Kusuki, Jiaxin Qiao, Leonardo Badurina, Kim Berghaus, Temple He, Allic Sivaramakrishnan, Julio Martinez, Clara Murgui, Ryan Plestid, Lorenz Eberhardt, Argha Mondal, Yixin Xu, Elliott Gesteau, Ritama Paul, Bratati Patra, Souvik Dutta, Pinaki Banerjee, Diptarka Das, Sara Murciano and Aron Hillman and many more. Some of these connections grew into long-term collaborations; others became lasting friendships. Together, we shared not just ideas and equations, but meals, travels, frustrations, and celebrations. In many ways, this network of people—spread across institutions and continents—became as important to my scientific growth as any single result or paper.

A Natural Next Chapter

As these threads came together, one realization became increasingly clear to me: the questions that continue to motivate my work live most naturally at the boundary between physics and mathematics. They demand physical intuition, but they also require mathematical sharpness—a willingness to push consistency to its limits and to follow the consequences wherever they lead.

That realization made the next step in my journey feel natural rather than abrupt. I am now a junior professor at the Institut des Hautes Études Scientifiques (IHES), an institute with a long tradition of precisely this kind

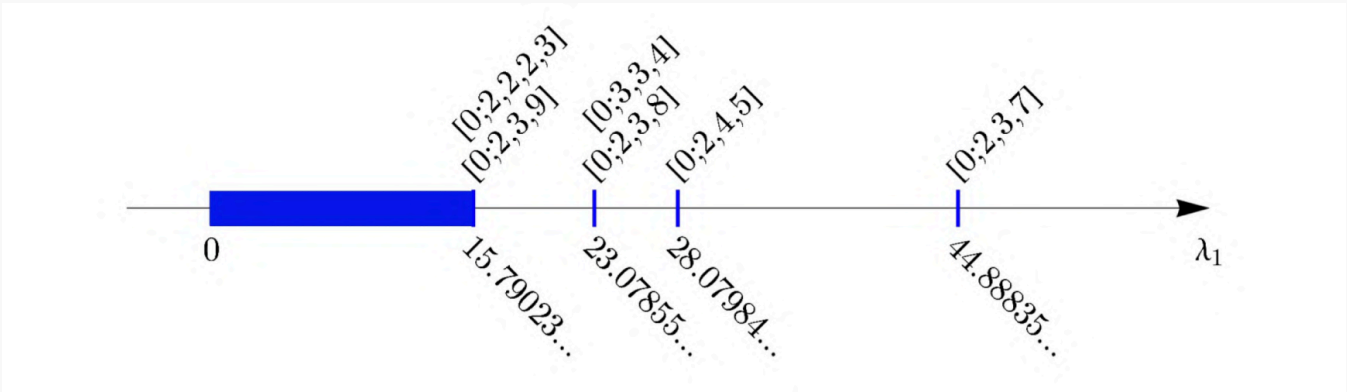


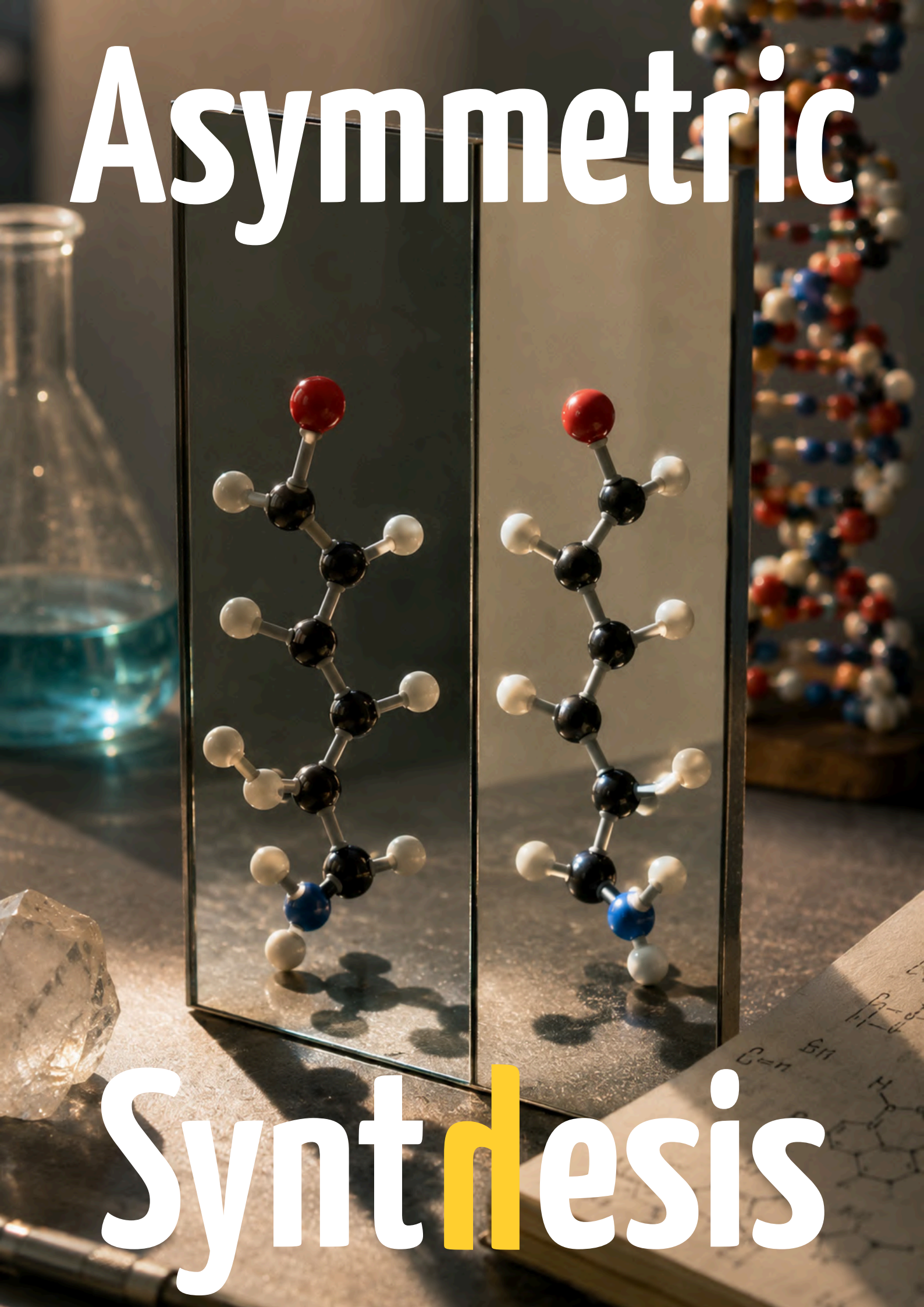
FIG 4 : *As we scan over various hyperbolic surfaces, the first non trivial eigenvalue of Laplacian takes the value, denoted with blue, on the real line. The numbers on top inside the square bracket are extit{names} of the surface, signifying the topological type. Figure taken from arXiv:2111.12716[hep-th].*

of cross-disciplinary thinking. IHES is a place where ideas are given time to mature, where mathematicians and physicists interact daily, and where questions about structure, universality, and rigor are part of the common language. Long before I arrived, its intellectual atmosphere had already shaped my work through the influence of people whose approaches I deeply admired.

What draws me most strongly to IHES is not a single research direction, but a way of working. It is an environment where foundational questions are not treated as detours, but as central pursuits, and where tools are free to migrate across fields when they illuminate new structure. For someone interested in how symmetry, consistency, and asymptotics conspire to shape quantum theories, it feels like a natural home.

At the same time, this chapter is not an endpoint. In Fall 2026, I will return to India to join the Tata Institute of Fundamental Research (TIFR), Mumbai, as a Reader. I see this move as a continuation of the same intellectual journey—bringing ideas shaped across institutions and disciplines back into a vibrant scientific community, and contributing to a growing dialogue between physics and mathematics.

FIG 5 : *Friends and collaborators: with Subham and Jiaxin at Iguazu, with Brato and Shouvik in Bengaluru, with Dalimil near Eiffel Tower, with Shreya and Brato in Bengaluru.*


Asymmetric
Synthesis

Overview of Asymmetric Synthesis & the Development of a Hybrid Catalytic System

Dr. Satavisha Kayal *Assistant Professor, IISER Pune*

Reviewed By: Debanuj Chatterjee

Jun 05, 2026

From the mirror-image molecules that distinguish medicines from poisons to the catalysts that make modern drug synthesis greener and more efficient, chirality lies at the heart of chemistry. Discover how hybrid catalytic systems are opening new frontiers in asymmetric synthesis, enabling the sustainable creation of life-saving molecules with remarkable precision.

Satavisha was born and raised in Sarisha, South 24 Parganas, West Bengal. Satavisha earned her doctoral degree in 2017 at IISc, Bangalore, specializing in Asymmetric Organic Synthesis. After her PhD, she joined as a postdoctoral fellow at Tohoku University, Japan, and later worked at the University of Florida, USA, as a postdoctoral researcher. Before joining IISER Pune in 2025, Satavisha served as an Assistant Professor at IIT Dharwad for a year.
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Website: https://skayal3.wixsite.com/skayal

Overview

Life is dominated by dissymmetrical actions. I can foresee that all living species are primordially, in their structure, in their external forms, functions of cosmic dissymmetry.

– Louis Pasteur

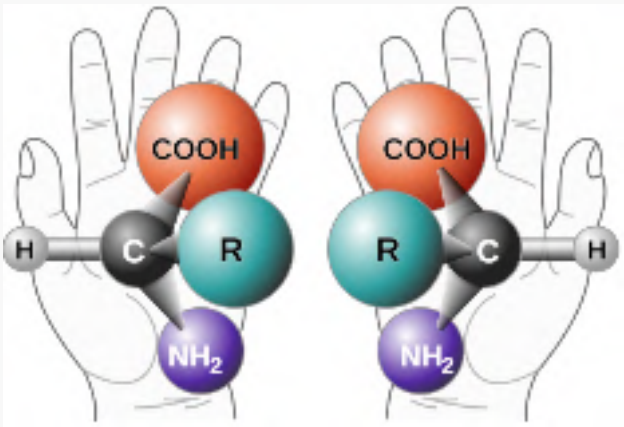

FIG 1 : *Two enantiomers of a chiral compound are mirror images of each other, that cannot be superimposed*

These visionary words, written by Louis Pasteur more than 100 years ago, have had a profound impact on the development of stereochemistry. The term "dissymmetry" is now known as "chirality" in modern chemistry or "handedness". Like a pair of hands, the two enantiomers of a chiral compound are mirror images of each other that cannot be superimposed. In 1801, French mineralogist Haüy first observed the phenomenon of chirality in quartz crystals. Later, in 1848, Louis Pasteur discovered clear evidence of chirality, demonstrating that it can rotate plane-polarized light. [2]

Since then, chirality has been recognized as a fundamental property of most three-dimensional objects. Despite having identical physicochemical properties—such as melting point, solubility, chromatographic retention time, and infrared (IR) and nuclear magnetic resonance (NMR) spectra—enantiomers can behave differently under external chiral influences. Furthermore, different enantiomers may exhibit distinct tastes, odors, and, most importantly, varying pharmacological effects. This underscores the critical significance of chirality in areas such as drug development and molecular biology. For example (R)-(+)-asparagine has sweet taste whereas (S)-(-)-asparagine is bitter (Figure 2). [3]

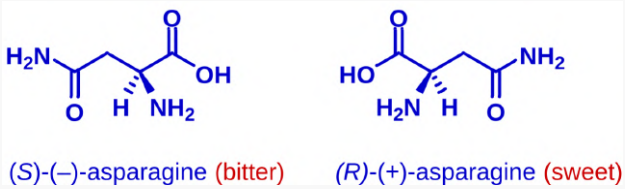

FIG 2 : *(R)-(+)-asparagine has sweet taste whereas (S)-(–)-asparagine is bitter*

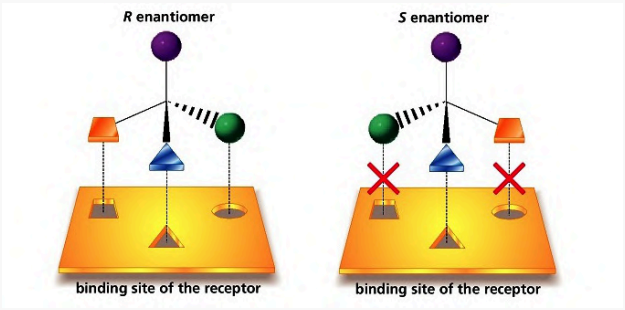

FIG 3 : *Two enantiomers of a drug often interact differently with receptors*

Naturally occurring biological macromolecules in living systems mostly exist in a single enantiomeric form. Consequently, only the biologically active enantiomer can effectively interact with its specific receptor. Thus, the two enantiomers of a drug often interact differently with receptors. Since human enzymes and cell surface receptors are themselves chiral, each enantiomer of a drug may be activated, absorbed, or degraded differently.

For example, dopamine is an effective drug for Parkinson's disease and is formed from (S)-(−)-DOPA via in vivo decarboxylation by the enzyme (S)-(−)-DOPA decarboxylase. This enzyme discriminates between enantiomers and specifically decarboxylates only the (S)-enantiomer of DOPA. Therefore, it is essential to administer DOPA in its pure (S)-form. Administration of racemic DOPA (rac-DOPA) would result in the accumulation of (R)-(+)-DOPA, as this enantiomer cannot be metabolized by the human body. [4]

Therefore, the enantiomeric discrimination is a remarkable feature of biological systems, making chirality a central concept in organic synthesis. As a result, the preparation of drugs, natural products, food additives, and flavoring agents in enantiopure form is highly desirable. Traditionally, enantiomerically pure compounds are obtained by resolving racemic mixtures, but this approach is inefficient because the undesired enantiomer must be discarded. To address this issue, asymmetric synthesis was developed, allowing achiral or prochiral starting materials to be converted into chiral products using a chiral environment, thereby enabling the efficient production of enantioenriched compounds.

Asymmetric synthesis can be classified into four major categories: (a) substrate-controlled methods, (b) auxiliary-controlled methods, (c) reagent-controlled methods, and (d) catalyst-controlled methods. The first three methods require either valuable chiral reagents or chiral substrates in stoichiometric amounts, which makes the processes expensive. In contrast, catalyst-controlled asymmetric synthesis—often employing chiral catalysts—offers a more economical and sustainable approach, as only catalytic amounts of the chiral source are needed. As a result, catalyst-controlled methods have become increasingly important in the development of practical and scalable asymmetric syntheses.

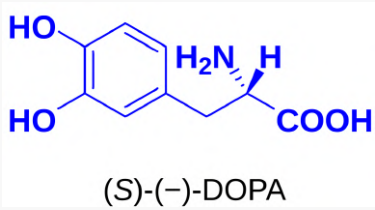

FIG 4 : *Dopamine is formed from (S)-(-)-DOPA*

Catalyst-controlled methods can be classified into three main categories based on the nature of the catalysts used:

1. biocatalysis
2. metal catalysis and
3. organocatalysis.

My research interests centre on multiple facets of organocatalysis, encompassing Brønsted acid catalysis, Lewis base catalysis, and phase-transfer catalysis. I am also dedicated to advancing novel hybrid catalytic systems by integrating metal catalysts with organocatalysts.

Development of a hybrid catalytic system

Much effort has been devoted to the efficient and selective synthesis of enantioenriched molecules due to the growing demand for a wide range of chiral organic compounds, including pharmaceuticals and functional materials. The development of advanced molecular transformations is crucial for enabling rapid and effective access to these enantioenriched molecules with high efficiency and selectivity. Furthermore, the construction of environmentally benign systems —thereby minimizing waste and conserving energy— should be a priority in their production. In this context, catalysis using small organic molecules, known as organocatalysis, has garnered significant attention over the past two decades. Organocatalysis enables efficient acceleration of fundamental organic transformations using catalytic amounts of organic molecules, offering a sustainable and versatile approach in modern synthetic chemistry.

Among the various organocatalysts developed, chiral Brønsted acid catalysts—especially chiral phosphoric acids—have received significant attention. A wide range of enantioselective transformations has been successfully accomplished using chiral phosphoric acids (I) and their derivatives. [1] Pioneering work by Professors Akiyama and Terada has established the foundation of this research area, and they continue to make substantial contributions that expand the scope of chiral Brønsted acid catalysis.

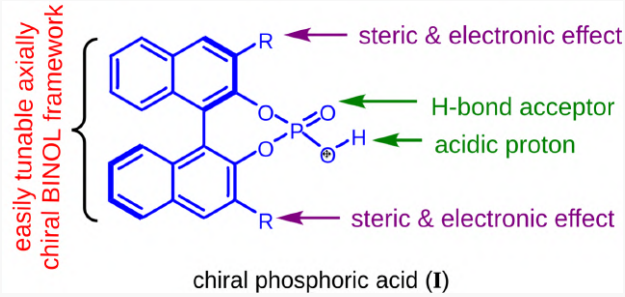

FIG 5 : *A wide range of enantioselective transformations has been successfully accomplished using chiral phosphoric acids (I) and their derivatives*

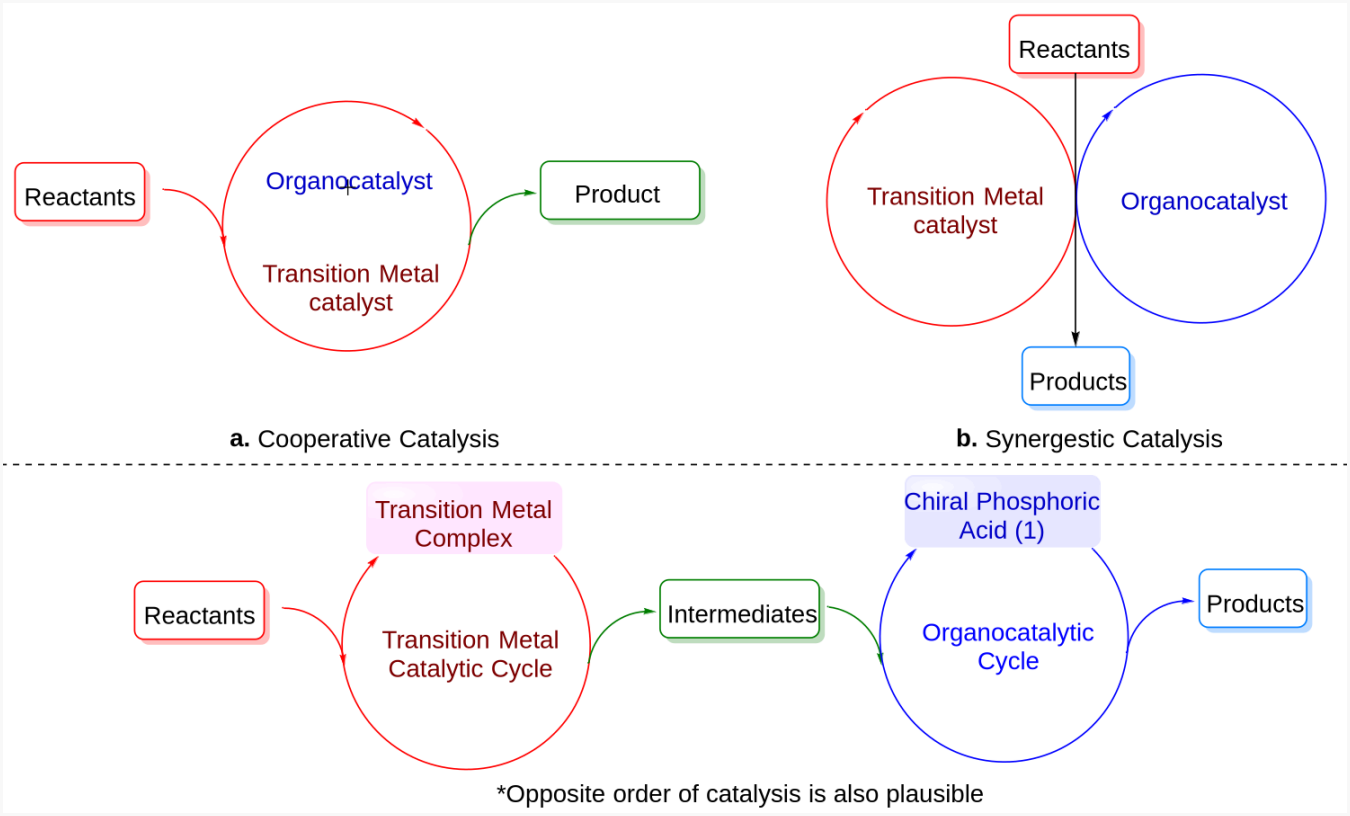

FIG 6 : *The concept of **a)** cooperative catalysis; **b)** synergistic catalysis and **c)** relay catalysis*

In contrast, catalysis by transition metal complexes has been applied to a broad range of organic transformations and occupies a privileged position in synthetic organic chemistry. Significant research on catalysis has centred on the use of metal complexes to activate a variety of chemical bonds. In recent years, with the idea of taking advantage of both of these catalytic approaches, metal complexes and organic molecules have been combined in cooperative binary catalytic systems, namely hybrid catalysis, which has attracted much attention as it could potentially enable highly efficient and/or unprecedented transformations in a one-pot operation (Figure 6). Indeed, excellent transformations have been established by taking advantage of both of these catalytic approaches, where two types of catalyst combinations have been developed in hybrid catalysis. One is that each reactant is activated simultaneously by one type of catalyst; for instance, a metal catalyst is used to activate the nucleophile while an organocatalyst is used to activate the electrophile in a cooperative manner (Figure 6a & 6b).

The other is the consecutive transformation using a binary catalytic system, that is, relay catalysis for a multistep sequence in which each catalyst promotes one type of reaction in a sequential manner. The later binary catalytic system, namely relay catalysis, is attractive with respect to achieving multistep transformations in one pot (Figure 6c).

Although several combinations between transition metal complexes and chiral phosphoric acids are possible, the efficient hybrid system is achieved under the following conditions:

1. avoiding the deactivation of catalyst each other
2. establishing the relay catalytic system efficiently.

Delightfully, the phosphoric acid catalysts are less coordinated ligand for metal species and hence deactivation of metal catalysts would be avoided in most cases. In addition, chiral phosphoric acid (I) is relatively inert to oxidation and reduction conditions. Hence phosphoric acid (I) can apply to redox reaction catalyzed by transition metal complexes. Although a variety of transformations would be expected in the proposed hybrid catalytic system, we focused on the utilization of transition metal-hydride complexes because these are powerful and efficient catalyst for the carbon-carbon multiple bond isomerization. We envisioned applying this attractive transformation to combine with the chiral phosphoric acid catalysis (Figure 7).

Importance of the proposed hybrid catalytic system

We envisioned relay hybrid catalysis by the combination of transition metal catalysts and chiral phosphoric acid catalysts (I), in which highly efficient and/or unprecedented transformations would be established in a one-pot and stereoselective manner. The key feature of the proposed relay hybrid catalytic system is that the number of batch operations is reduced to suppress the formation of waste materials. In addition, the generation of reactive intermediates in situ is achieved for further transformations, and the method is beneficial in terms of maintaining the reactive intermediate at a low concentration to avoid the formation of byproducts.

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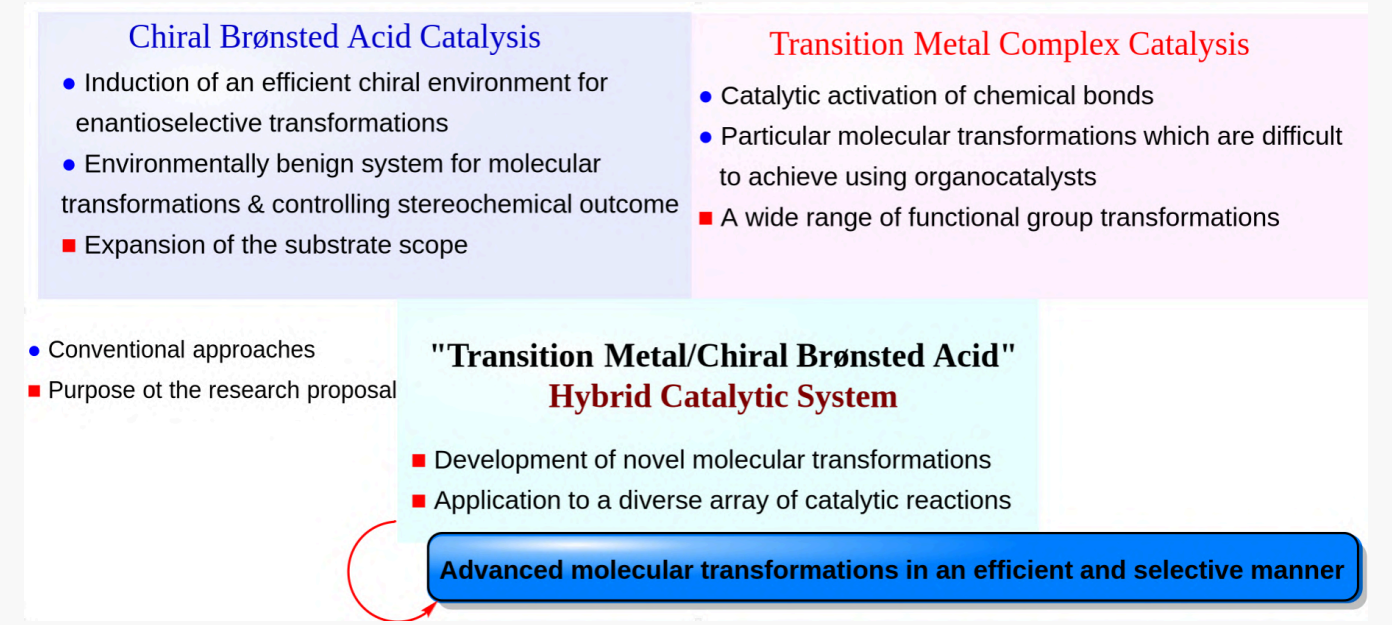
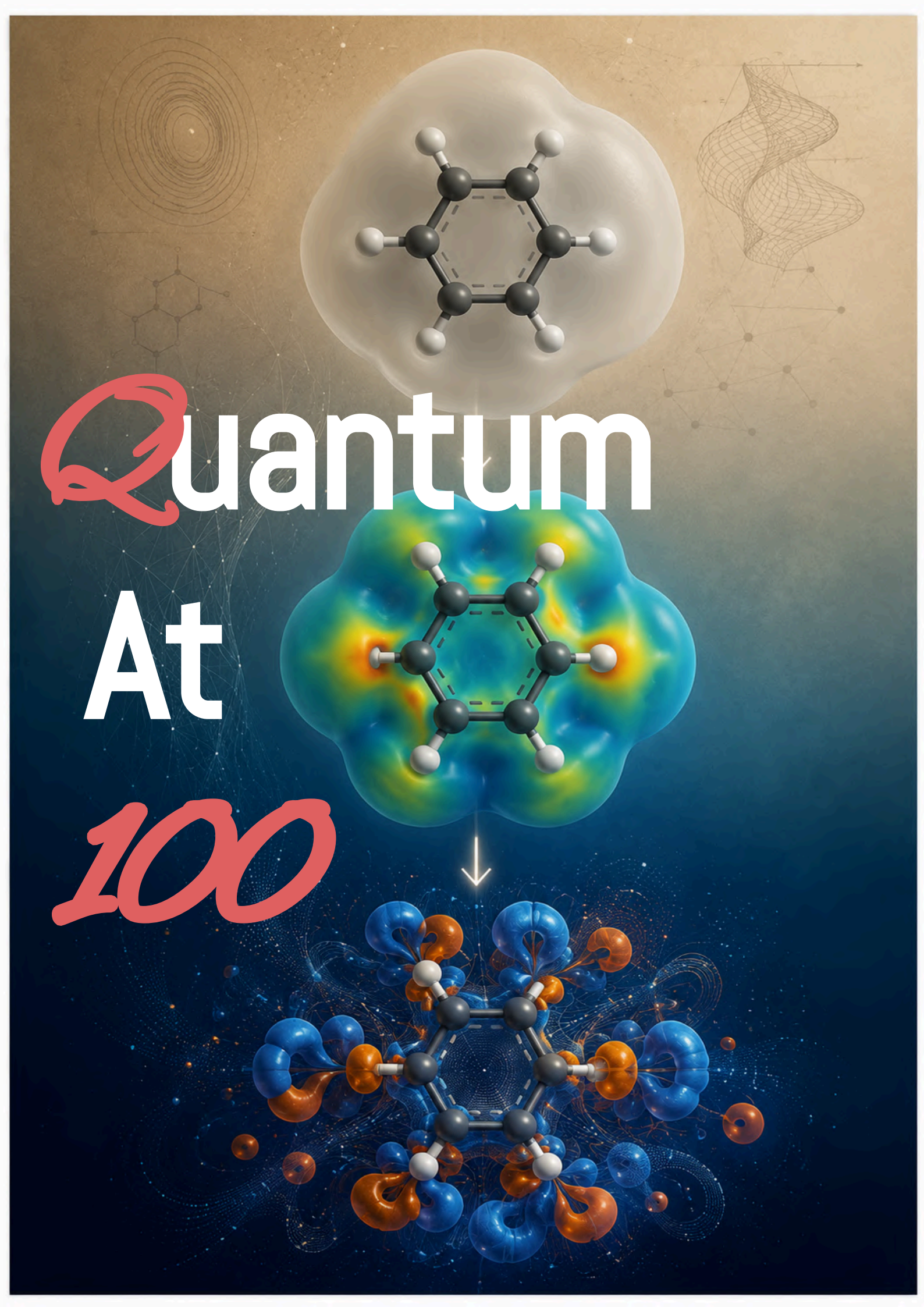


FIG 7 : *Advanced molecular transformations by "transition metal/chiral Brønsted acid" hybrid catalytic system*


Quantum
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100

Quantum at 100: From Heisenberg's Revolution to Modern Science

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Apr 29, 2026

Reviewed By: *Archita Sarkar, Dishari Dasgupta*

What if the electron never truly orbited the nucleus, not because its path was too small to be observed, but because the very idea of a definite path was the wrong question? A century ago, quantum mechanics forced science to forsake the familiar language of classical motion and rethink how nature itself should be described. This article traces the remarkable journey- from Heisenberg's rejection of electron orbits to the quantum theories of chemical bonding, electron correlation, and modern computational science, revealing how one conceptual revolution transformed our understanding of atoms, molecules and materials.

Dr Anu Arora is a postdoctoral researcher at Ashoka University, Sonepat, and she works with Prof. Sourav Pal. Her research interests include computational quantum material science, particularly first-principle studies of spin-polarised phenomena and their applications in spintronics, quantum materials and energy conversion applications.

Prof. Sourav Pal is a leading theoretical and computational chemist, right now serving as Head of the Chemistry Department at Ashoka University, Sonepat. His work focuses on the development of new methodologies and conceptual frameworks in many-body electronic structure theory, density-based approaches to chemical reactivity, along with the investigation of catalytic as well as hydrogen storage materials, through computational material science.

What we observe is not nature itself, but nature exposed to our method of questioning. — Werner Heisenberg

The Birth of New Science (1925)

At the beginning of the 20th century, classical physics, comprising Newtonian mechanics and Maxwell's electrodynamics, was regarded as a nearly complete theoretical framework. The two pillars of physics seemed complete until experimental observations at microscopic scales revealed their limitations.

One of the earliest inconsistencies arose with the failure of blackbody radiation. According to the classical theory, Rayleigh–Jeans law, the emitted energy would diverge at high frequencies, becoming infinitely large, resulting in the ultraviolet catastrophe [1]. To overcome this problem, Max Planck proposed in 1900 that electromagnetic radiation is exchanged in discrete energy packets, or quanta, with energy [2]

$$E = h\nu.$$

Shortly thereafter, Albert Einstein extended this concept to light, explaining the photoelectric effect by introducing light quanta (photons), thereby establishing the particle nature of electromagnetic radiation [3].

Despite these successes, the structure of the atom remained partially understood. The Bohr–Sommerfeld model (1913–1916) introduced a semi-classical picture in which electrons occupy discrete orbits around the nucleus [4] and transition between them via quantised angular-momentum conditions,

$$\int pdq = nh/2\pi,$$

[5] ($n = 1, 2, 3\ldots$). While this model successfully explained the hydrogen spectrum, it could not accurately describe fine spectral properties like anomalous Zeeman effect [6], Stark splitting [7], or transition intensities, indicating the absence of a theoretical foundation.

A major turning point occurred in 1925, when Werner Heisenberg rejected the classical idea that electrons move along well-defined trajectories around the nucleus. Instead, he argued that the atomic theory should be constructed entirely from quantities that can be experimentally observed. In his correspondence with Wolfgang Pauli, Heisenberg criticised the orbital picture of electrons and proposed that atomic behaviour should be described using measurable spectroscopic quantities such as transition frequencies and spectral intensities. Expressing his discontent with classical orbitals, Heisenberg explicitly stated:

All of my pitiful efforts are directed at completely killing off the concept of orbits, which, after all, cannot be observed, and replacing it with something more suitable.

In this new approach, physical quantities were represented through a transition between quantum states rather than through a definite electron path. The

central aspect of the new formalism was that the ordering of operators is essential, such that $xy \neq yx$ [8-9]. The formalism was later extended into matrix multiplication by Max Born and Pascual Jordan, who represented physical observables as matrices acting on quantum states. This new theory successfully explained atomic spectra, including discrete energy levels and transition rules.

Although quantum mechanics initially emerged to explain atomic phenomena, it soon developed into a broader framework for understanding systems across multiple length scales, ranging from electrons to molecules to material and biological systems.

From Orbits to Bonds: Birth of Quantum Chemistry (1927)

With quantum mechanics, chemists had a new question: *how do atoms combine and form stable molecules?*

Before the 1920s, the bonding was described through empirical valence rules and structural observations, without a rigorous microscopic explanation. There was no microscopic explanation for why two hydrogen atoms form a stable molecule. In 1927, Walter Heitler and Fritz London presented their study on H2 [12] using the wave mechanics introduced by Erwin Schrödinger. The electronic behaviour of the molecules is governed by the time-independent Schrödinger equation

$$H\Psi = E\Psi,$$

where H is the Hamiltonian operator, Ψ is a two-electron wavefunction, and E is the corresponding energy eigenvalue. For the hydrogen molecule, the full molecular Hamiltonian in atomic units ($\hbar = m_e = e = 1$) takes the form:

$$\hat{H} = -\frac{1}{2}\nabla_1^2 - \frac{1}{2}\nabla_2^2 - \left(\frac{1}{r_{1A}} + \frac{1}{r_{1B}} + \frac{1}{r_{2A}} + \frac{1}{r_{2B}}\right) + \left(\frac{1}{r_{12}} + \frac{1}{r_{AB}}\right)$$

where ∇_1^2 and ∇_2^2 are the Laplacian operators representing the kinetic energy of electrons 1 and 2, respectively, r_{1A}, r_{1B}, r_{2A} and r_{2B} denote the distances of each electron from nuclei A and B, r_{12} is the interelectronic distance, and R_{AB} is the internuclear separation. The first two terms are kinetic energy, the next four terms are electron-nuclear attraction, and the last two terms are electron-electron and nuclear-nuclear repulsion,

As atoms come close together, their electronic wave functions interact and mix. Because electrons are indistinguishable fermions, the total electronic wavefunction must satisfy the antisymmetric condition imposed by the Pauli exclusion Principle. This produces two distinct arrangements:

- **Bonding state (symmetric spatial part, spin singlet)**: the overlap of electronic wavefunctions increases electron density in the region between the nuclei. This lowers the total energy and stabilises the molecule.
- **Antibonding state (antisymmetric spatial part, spin triplet)**: the overlap generates a nodal region between the nuclei, decreasing electron density in the internuclear region. As a result, the energy increases and the molecular configuration become unstable.

The energy lowering in the bonding state comes from the quantum mechanical exchange effect, a direct consequence of anti-symmetrisation of the wavefunction. This was the first quantum mechanical explanation of the covalent bond, and it became the basis of Valence Bond Theory, making the shift from qualitative valence rules to quantitative solutions of the Schrödinger equation.

Solving the Molecular Problem: The Born–Oppenheimer Approximation (1927)

Understanding bonding in principle was one part. Solving the Schrödinger equation for real molecules, with all electrons and all nuclei interacting simultaneously, remained a serious challenge. Born and Oppenheimer introduced a powerful simplification based on physical observation. The nuclei are approximately $10^3 - 10^4$ times heavier than electrons. This means electrons respond almost instantaneously to any nuclear motion, while nuclei move on a much smaller timescale. The two motions are nearly decoupled.

This approximation enables the total molecular wavefunction to be separated into two simpler parts:

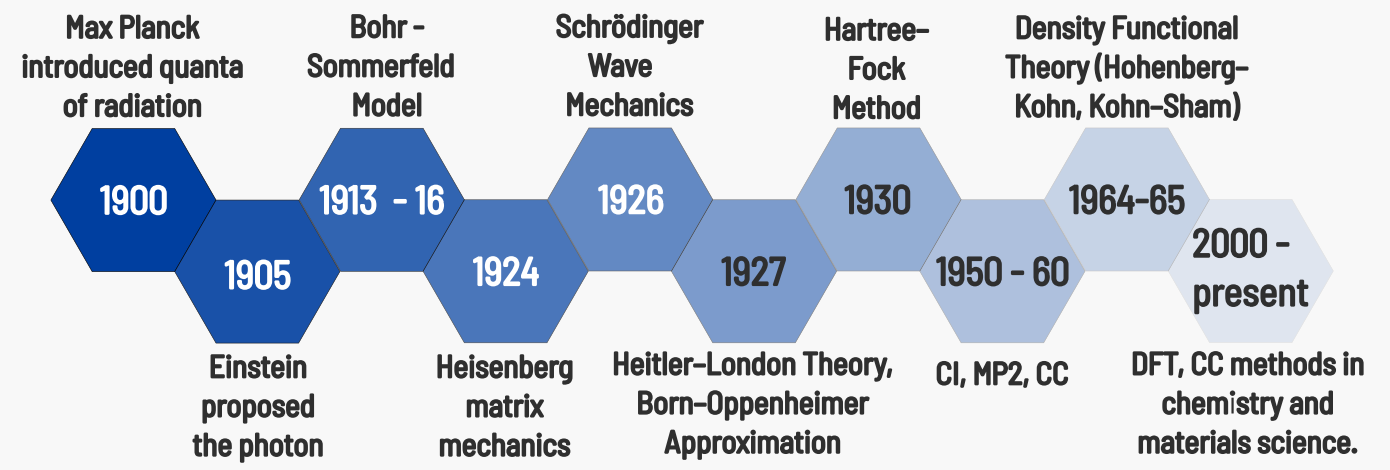

FIG 1 : *Timeline of key milestones in quantum mechanics and computational chemistry, from Max Planck's radiation quanta to modern approaches including Density Functional Theory and advanced post-Hartree–Fock approaches for atomic and molecular systems.*

one associated with electronic motion and the other describing the nuclear motion.

- **Electronic part**: Solve for electrons in a fixed nuclear framework to obtain $E_e(R)$.
- **Nuclear part**: Use $E_e(R)$ as an effective potential governing nuclear motion.

This separation is the foundation on which quantum chemistry is built. It converts an intractable coupled problem to a manageable sequence of calculations.

The Hartree–Fock Method and the "Mean-Field" Approximation

Even after fixing the nuclear positions within the Born-Oppenheimer approximation, the resulting electronic problem remains highly nontrivial. The motion of one electron is inherently coupled to that of all others through Coulombic interactions, making the many-electron Schrödinger equation intractable. To render the problem, approximate methods must be employed, of which Hartree-Fock (HF) is among the most foundational. The HF method was developed by Hartree in 1927-1928 and rigorously reformulated by Fock and Slater in 1930 [14-15].

The central idea of the theory is based on a simple assumption that, instead of explicitly treating the instantaneous interaction of every electron with all other electrons, each electron is expected to move independently within a mean field generated by the remaining electrons. Under this approximation, the many-electron Schrödinger equation is transformed into a set of coupled single-electron equations that can be solved self-consistently.

In the HF framework, the N-electron wavefunction is expressed as a Slater determinant[16], a determinant of a matrix of single-electron orbitals. This construction automatically satisfies the antisymmetry property, i.e. swapping any two rows of a determinant flips its sign. This enforces the Pauli exclusion principle.

The resulting HF equations are then solved using an iterative method in which an initial guess for the electronic density is made, from which an effective potential is constructed. Then the resulting equations are solved for new orbitals, and this procedure is repeated until self-consistency is reached.

HF treats electron-electron repulsion on average. But the real electrons correlate; when one electron is at a given position, the other instantaneously avoids it. This dynamical correlation is completely absent from HF theory because the wavefunction is restricted to a single Slater determinant [16]. Thus, the method systematically overestimates the electronic ground-state energy. The missing contribution is called correlation energy, and recovering this energy became the motivation for developing more advanced quantum chemistry methods.

Electron Correlation and Beyond Hartree-Fock (1960)

From 1960 onwards, the central challenge of quantum chemistry became recovering electron correlation, the instantaneous correlation motion, the correlated motion of electrons that HF misses. Two broad families of methods emerged: wavefunction (which work directly with Ψ) based approaches and density-based approaches (which work with $\rho(r)$)

Density Functional Theory

Density Functional Theory (DFT) is one of the most widely used theoretical frameworks in modern computational chemistry, material science and solid-state physics. This fundamental principle was first formulated by Pierre Hohenberg and Walter Kohn [17]. Its central insight is both simple and non-obvious. The complete information about the ground state of many-electron systems, including its energy and other properties, is fully encoded in the electron density $\rho(r)$, which depends only on 3D position coordinates in space. So, in principle, there is no need of 3N dimensional wavefunction. Hohenberg-Kohn proved that the functional $E[\rho]$ exists but did not provide a way to compute it.

Thus, **Kohn and Sham** introduced an approach in which the interacting many-electron system is reformed by a fictitious system of non-interacting electrons moving in an effective potential [18]. Although this system is hypothetical, it produces the exact ground-state electron density of the actual interacting system. Within this framework, the total energy is written as

$$E[\rho] = T_s[\rho] + \int V_{\text{ext}}\rho + E_H[\rho] + E_{\text{xc}}[\rho],$$

where, $T_s[\rho]$ is the kinetic energy of an auxiliary system of non-interacting electrons, $E_H[\rho]$ is the classical Hartree term describing electron–electron electrostatic repulsion, and $E_{\text{xc}}[\rho]$ is the exchange–correlation functional.

The corresponding Kohn–Sham equations take the form:

$$\left[-\tfrac{1}{2}\nabla^2 + V_{\text{eff}}(r)\right]\varphi_i(r) = \varepsilon_i\varphi_i(r),$$

where $V_{\text{eff}}(r)$ is an effective potential and $\varphi_i(r)$ is the i-th Kohn-Sham orbital and ε_i is the corresponding Kohn-Sham orbital energy eigenvalue. The electron density is therefore constructed from the orbitals as follows:

$$\rho(r) = \sum_i |\varphi_i(r)|^2.$$

These equations are solved iteratively until convergence, yielding a stable ground-state density and energy of the system. This procedure is called the self-consistent field (SCF) method.

Jacob's Ladder: Systematic Improvement of DFT

To systematically enhance the accuracy of density functional calculations, John P. Perdew introduced the concept of Jacob's ladder[19], which organises density functional approximations into a hierarchy of increasing sophistication:

- Local Density Approximation (LDA): depends only on local density
- Generalised Gradient Approximation (GGA): incorporates both density and its spatial gradients
- Meta-GGA: further includes quantities such as the kinetic energy density

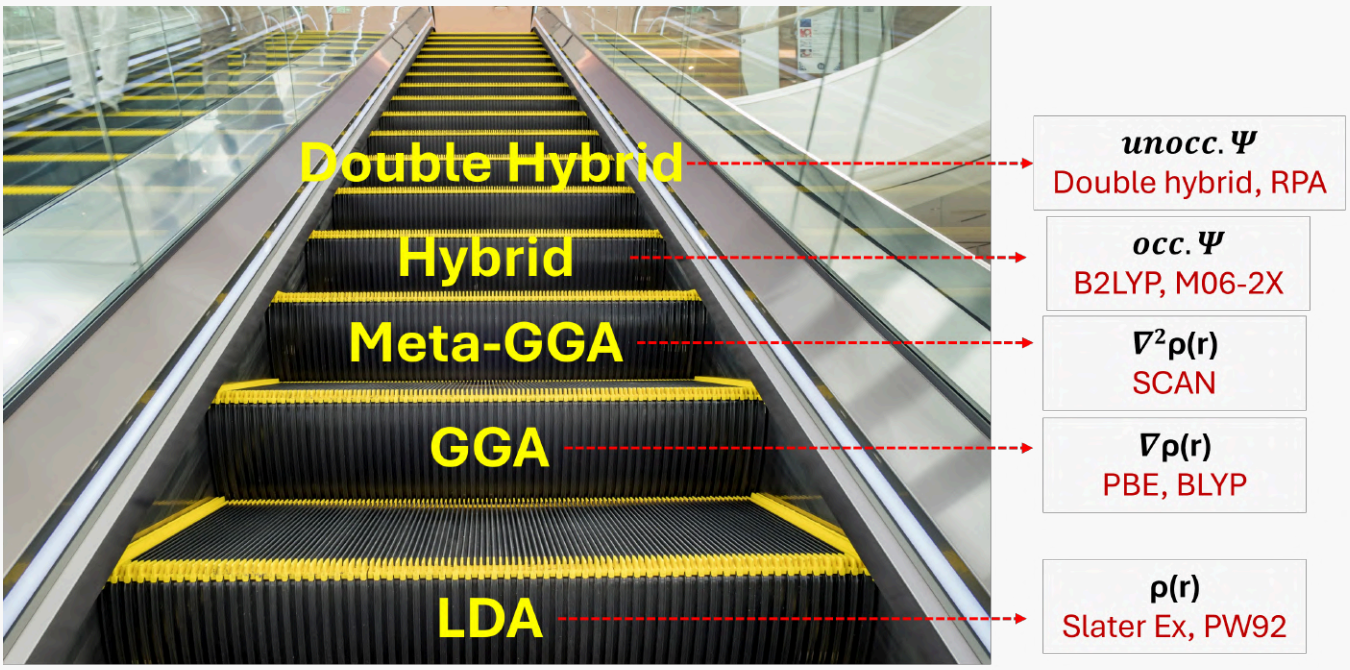

FIG 2 : *Schematic representation of Jacob's ladder in DFT, approximations from LDA → GGA → meta-GGA → hybrid → double hybrid, showing increasing accuracy.*

- Hybrid functionals: combine DFT exchange with exact exchange
- Double hybrids: include perturbative correlation corrections.

As we move up Jacob's ladder, more physical information is included, improving the description of exchange-correlation. Although DFT relies on approximate functionals, it offers an excellent balance between computational accuracy and cost (approximately N^4 scaling, where N represents the number of atoms). Therefore, it is widely used in studying larger molecules, solids and condensed matter systems.

Coupled Cluster and Relativistic Coupled Cluster

For highly accurate calculations, especially when electron correlation effects are substantial, Coupled Cluster (CC) Theory was developed as one of the most compelling and systematically improvable approaches. The method is widely recognised as the benchmark, or "gold standard" for molecular energies and related properties.

Within the CC scheme, the correlated wavefunction is expressed using an exponential ansatz in the form of

$$| \Psi_{cc} \rangle = e^{T} | \Phi_0 \rangle,$$

where T is the cluster excitation operator that accounts for electron correlation effects through a hierarchy of excitations built upon the reference Slater determinant $| \Phi_0 \rangle$ [20]. In practical applications, the expansion is commonly truncated to obtain computationally feasible methods such as coupled cluster single and double excitations (CCSD) and coupled cluster single and double excitations including perturbative triple excitations (CCSD(T)). These methods frequently yield molecular energies and related properties with near experimental accuracy, especially for small and medium-sized molecular systems.

Figure 3 presents the computational scaling of widely used electron structure methods. The steep growth in computational expense with increasing system size N underscores the difficulty of extending highly accurate correlation-based approaches to large molecular systems.

The standard CC starts from a single HF reference, which assumes one electronic configuration dominates. This breaks for systems exhibiting near-degeneracy effects, such as bond dissociation or strongly correlated electronic states. Thus, multireference extensions of CC become necessary. It captures both static and dynamic electron correlation effects within a unified framework[21-22].

Beyond energies, CC theory is extended to compute molecular properties analytically, dipole moments, polarizabilities, NMR shielding, spectroscopic constant and more. The Z-vector method makes this an efficient method[23]. It solves a linear response equation and computes all first-order properties rather than differentiating the CC wavefunction.

For systems having heavy elements, relativistic effects become necessary for achieving accurate theoretical predictions. The most famous example is that gold and silver are predicted to exhibit similar chemical and optical properties. But the relativistic correction of the 6s orbital of gold results in the change in s-d orbital energy gaps, which directly explains gold's anomalous optical appearance and chemical behaviour. Relativistic effects are also crucial in phenomena such as parity non-conservation [24] and electron electric dipole moment studies in heavy molecules like HgF [25].

To consistently incorporate both relativistic and electron correlation effects in a consistent manner, CC theory is

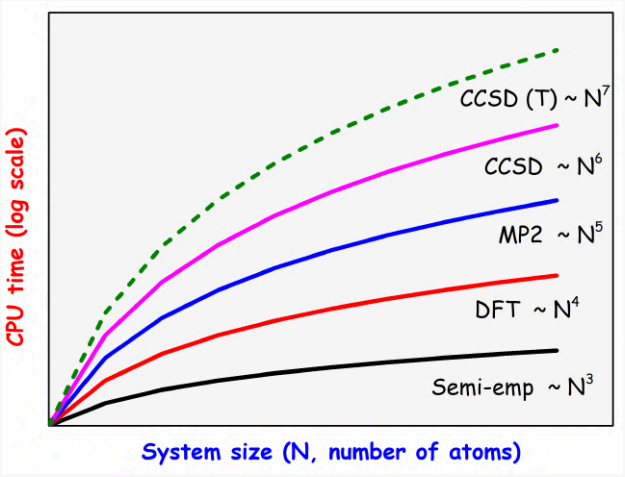

FIG 3 : *Comparison of computational scaling with increasing system size for electronic-structure methods. The log of CPU time is plotted against the number of atoms N, showing characteristic polynomial scalings: semi-empirical methods ($-N^2$), DFT ($-N^4$), MP2 ($-N^5$), CCSD ($-N^6$), and CCSD(T) ($-N^7$). The figure highlights the rapidly increasing computational expense of higher-accuracy correlated methods with system size.*

extended to the relativistic coupled cluster framework (RCC). Together with response theory approaches such as Z vector methods, RCC enables highly accurate calculations of spectroscopic and electromagnetic properties, including hyperfine constant, transition moments and parity violation interactions [26-27]. Consequently, relativistic quantum many-body methods have become indispensable tools in modern quantum science and precise quantum measurements.

Next Century of Quantum Mechanics

The modern quantum mechanics is increasingly moving towards highly accurate and scalable approaches based on advanced many-body methods such as CC theory and its relativistic extensions. These methods provide a rigorous description of electron correlation and chemical bonding, often achieving near experimental accuracy even for heavy element systems and strongly correlated materials. At the same time, machine learning techniques are being incorporated to accelerate electronic structure calculations while preserving first-principles accuracy. Overall, the field is evolving towards a combination of quantum many-body theory and data-driven methods, enabling reliable prediction of molecular and material properties.

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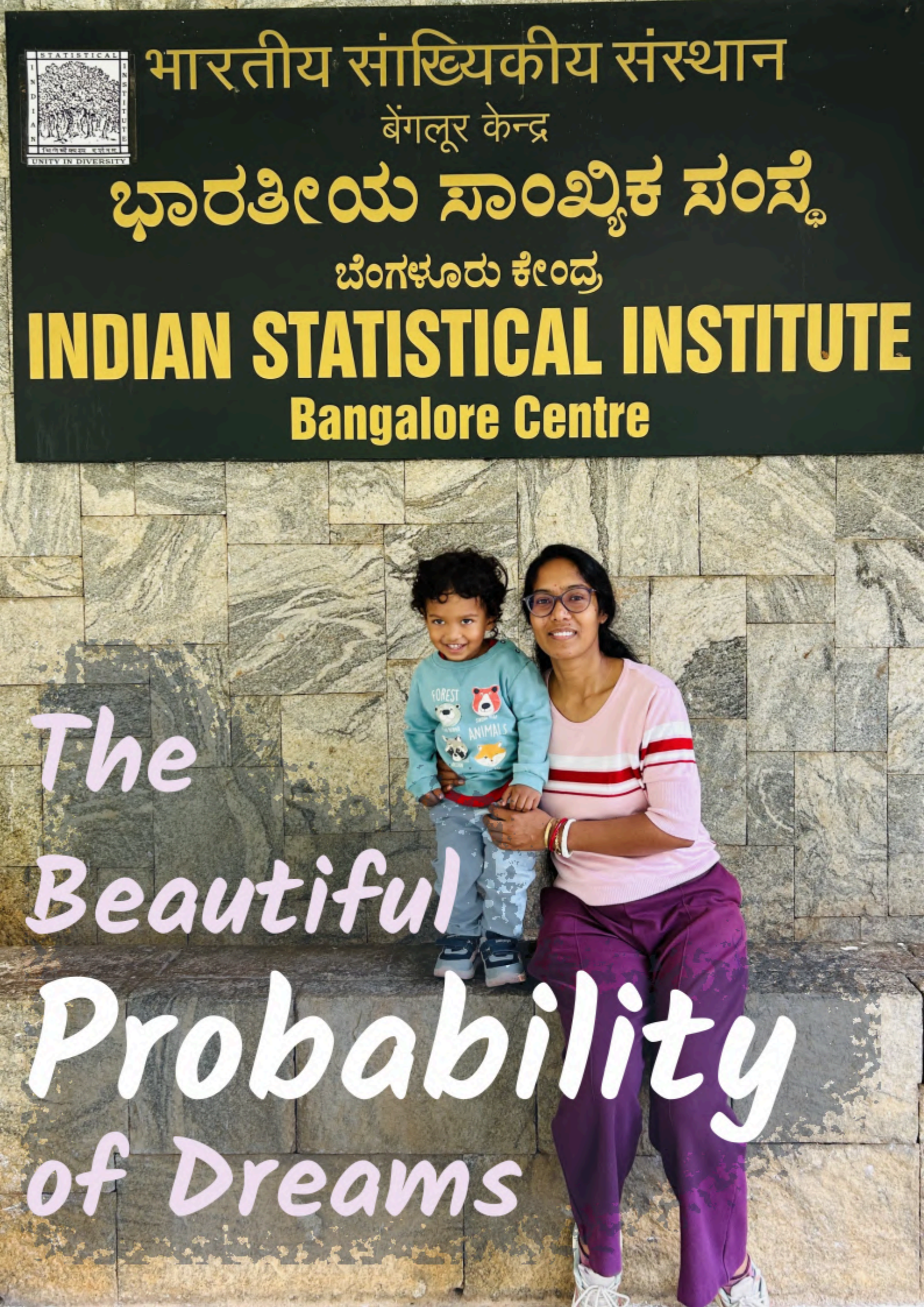
भारतीय सांख्यिकीय संस्थान
बेंगलूर केन्द्र
ಭಾರತೀಯ ಸಾಂಖ್ಯಿಕ ಸಂಸ್ಥೆ
ಬೆಂಗಳೂರು ಕೇಂದ್ರ
INDIAN STATISTICAL INSTITUTE
Bangalore Centre
The
Beautiful
Probability
of Dreams

The Beautiful Probability of Dreams: Journey to IISER Berhampur

Sangita Das *Department of Mathematical Sciences, IISER Berhampur*

Jun 19, 2026

Reviewed By: *Debanuj Chatterjee*

Growing up as a girl in a rural village, I never imagined I would end up where I am today. Now, as an Assistant Professor of Mathematics at IISER Berhampur, I look back and realise how simple the recipe for success truly is. My journey taught me that you can overcome almost any obstacle if you stay focused on your goals and surround yourself with good, supportive people. In this article, I want to share my personal story—not just to look back, but to remind young dreamers everywhere that where you start in life does not decide how far you can go.

Dr Sangita Das is an Assistant Professor in the Department of Mathematical Sciences at the Indian Institute of Science Education and Research, Berhampur. Her research focuses on developing probabilistic and statistical methodologies with applications in reliability engineering, risk analysis, and data-driven decision sciences.

Growing up in rural West Bengal, the traditional script for a girl's education was quite simple. I was expected to be no exception to this rule. However, during my 12th standard, logic interrupted that script. I found myself deeply drawn to science, specifically the absolute clarity of mathematical reasoning.

Determined to explore this further, I went on to pursue my Math Honours at Raja Peary Mohan College, Calcutta University. I didn't study the subject to fit into a pre-determined box; I studied it simply because I fell in love with how mathematics speaks at its own beat and beauty. This passion deepened during my Master's at IIEST Shibpur, which became the exact place where my interest pivoted from just absorbing textbooks to creating new knowledge through research.

Life, however, took its own turn. Following my Master's, I got married and faced a career break of around three years. In our society, a break like that often marks the quiet end of a woman's academic aspirations. But I was fortunate. My husband Dr. Sekhar Ghosh was a constant pillar of support throughout this transition. While our society often expects women to compromise, he constantly pushed me to pursue my goals. His belief in my abilities helped me overcome my self-doubt, giving me the confidence to bridge the career gap and take the next step. Both my husband and I shared a deep love for mathematics and a final aim to pursue research.

Starting My PhD In Statistics

With that shared strength, I returned to academia and began my Ph.D. at NIT Rourkela in Statistics. Though mathematical analysis was my first love, my Master's in Applied Mathematics at IIEST Shibpur pulled me in a different direction. During my coursework, things began to click differently. I realised that while mathematics provided the perfect language and structural framework, statistics provided the actual tools to solve real-world problems where nothing is certain. This practical connection—seeing equations directly solve real-life problems—became the exact motivation that pushed me to start my Ph.D. in Statistics.

I owe a massive debt of gratitude to my advisors, Dr. Suchandan Kayal and Dr. Debajyoti Choudhuri. They shaped my statistical fundamentals, keeping me ready for the global stage and transforming my curiosity into rigorous scientific inquiry.

The next chapters acted as major milestones that completely reshaped my research outlook. I had the opportunity to visit Ghent University in Belgium, and later, joined as a Visiting Scientist at Indian Statistical Institute (ISI) Bangalore. Every new campus brought a fresh perspective and a new way of looking at research. Working with different research groups didn't just expand my academic outlook—it showed me that the best science thrives on global collaboration and shared ideas.

After that, I served as an Assistant Professor in the Department of Mathematics at SRM University, Andhra Pradesh, for around one year. Teaching and interacting with young minds was a completely different experience. It forced me to look at mathematics from a whole new angle, adding a fresh and rewarding direction to my academic journey.

FIG 1 : *With B.Math Student, 2025 Batch at ISI Bangalore.*

To wrap up an incredible year of teaching, my personal and professional lives reached their biggest milestones simultaneously. First, I received the prestigious NPDF fellowship from ANRF, Government of India. This opened the doors to ISI Bangalore as an NPDF Post-Doctoral Fellow. Secondly, I became a mother.

Post-Doctoral Research As A New Mother

I started my Post-Doctoral study at ISI Bangalore with my newly born son. As a new mother, I found myself in a challenging situation, balancing my academic career and my responsibilities. But my husband, mentor Prof. Mohan Delampady and the entire ISI Bangalore community stood by me completely. Their support and understanding helped me get through that difficult time smoothly.

During this period, my interactions with him and Prof. Siva Athreya completely transformed my academic perspective. They supercharged my interest in statistical inference and inspired me to dive deep into the interface of stochastic ordering and inferential methodology. It truly drove me to ask fresh research questions that connected theoretical probability directly to practical, real-world problems. During this tenure, I also got the opportunity to teach B.Math students, which added a whole new dimension to my journey. It made me realise that mathematics and statistics are not just subjects to be read from textbooks—they are languages to be understood and used to connect with young minds.

My early research focused on stochastic comparisons of order statistics arising from independent and dependent observations. In particular, I have been interested in establishing stochastic inequalities using tools from vector and matrix majorization theory. I mainly developed ordering results of order random variables arising from general families of distributions and apply the established results in different fields like, reliability theory (to find better reliability systems, reliability bounds, see [2,4,6,7,9]), insurance analysis (comparing the extreme claim amounts, see [3,5,8]), auction theory (compare bid amounts in different types of auctions, see [2,6]). These mathematical frameworks provide powerful mechanisms for comparing random phenomena and understanding how heterogeneity, dependence, and parameter variations influence system behaviour. Such comparisons have important implications in diverse areas ranging from reliability engineering and actuarial science to insurance analysis and industrial applications in aeronautics and automotive systems.

During my Ph.D., I absolutely fell in love with reliability theory and survival analysis! These fields are all about figuring out exactly how long a system or a product can last before it hits a breaking point. Think of it like predicting exactly when a phone battery will finally give up, or tracking how long a life-saving medical treatment will keep a patient healthy. What completely hooks me is using solid, hardcore mathematics to map out how things behave over time. It is incredibly exciting to see how these equations empower us to make sharp, data-driven decisions—even when the real-world data is messy and incomplete!

My Research On Statistical Predictions

Today, my research focuses on reliability theory, survival analysis, stochastic ordering, and Bayesian analysis. At

FIG 2 : *With Prof. Bernard De Baets, Department of Data Analysis and Mathematical Modelling,Ghent University, during visit in 2022.*

its core, my work seeks to answer questions related to uncertainty. How can we compare systems whose future behaviour is uncertain? How can we predict reliability when complete information is unavailable? How can statistical methods help us make better decisions under risk?

To put it simply, reliability theory looks at how systems perform and how long they last—whether we are talking about engineering parts or complex communication networks. Survival analysis tackles similar questions, focusing on the exact time it takes for an event to happen. Then there is stochastic ordering, an area that interests me deeply, which provides the mathematical tools to compare uncertain quantities and balance risks. On top of that, Bayesian methods allow us to combine what we already know with fresh, observed data. This makes our final conclusions much more realistic and practical for the real world.

As my research progressed, I became increasingly interested in situations where the number of observations or system components is itself random. This transition naturally led me to study order statistics for the case of random number of observations, particularly random minima and maxima. While classical statistical theory often assumes a fixed sample size, many real-world systems operate under conditions where the number of observations, events, or components is inherently uncertain. Such uncertainty introduces new mathematical challenges and motivates the development of novel probabilistic methodologies.

Currently I am working on establishing rigorous stochastic comparisons among such random extremes under different distributional assumptions and dependence structures. By developing new stochastic inequalities and ordering results, I aim to understand how uncertainty in sample size, heterogeneity among components, and dependence among observations influence system performance and risk characteristics (see [9,10,11]).

The importance of stochastic ordering has grown significantly in recent years (see [1]). Modern societies increasingly rely on risk-sensitive systems, ranging from financial markets and insurance portfolios to transportation networks, healthcare systems, and critical infrastructure. At the same time, with the boom in artificial intelligence and machine learning, everyone is realising how important it is to measure uncertainty. As our predictive models get smarter, it is not enough to just guess the final result. We also need to understand the variations, the reliability, and the worst-case scenarios. This is exactly where stochastic ordering steps in. It provides us with a solid mathematical framework for comparing risks, evaluating different systems, and making smart decisions when things are uncertain.

Taking Stock

Moving forward, my main goal is to build new mathematical frameworks that help us make sense of uncertainty, no matter how complex the systems become. My long-term vision is to bring stochastic ordering, dependence modelling, and modern statistics together into one powerful approach. This will help us solve tough, real-world challenges across diverse fields like finance, public health, climate science, and new data technologies. Today, our world is completely interconnected, and dealing with uncertainty is part of everyday life. I deeply believe that developing solid, reliable math tools to compare and measure risks will

FIG 3 : *With Prof. Hans De Meyer, Department of Mathematics, Computer Science and Statistics, Ghent University, during visit in 2022*

play a massive role in future scientific breakthroughs and in helping society make smarter decisions

Today, standing as a faculty member at IISER Berhampur, I look back at that rural girl who never imagined to be here. I am reminded that a career break is not a full stop, and societal expectations are not boundaries. Mathematics gave me a voice, and my goal now is to help my students find theirs.

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Why
Giant
Dragonflies
Disappeared

Why Giant Dragonflies Disappeared

Aditya Choudhary *Little Angels School, Visakhapatnam*

Reviewed By: Debanuj Chatterjee

Jun 19, 2026

Millions of years ago, giant dragonfly-like predators with the wingspans of modern seagulls ruled the skies before mysteriously vanishing. While scientists have long blamed their extinction on plummeting atmospheric oxygen levels, new anatomical research suggests these ancient insects had plenty of respiratory capacity to spare. This article explores the fascinating possibility that the true culprits behind their demise were shifting prehistoric ecosystems and the evolutionary rise of agile, insect-hunting birds.

Aditya Choudhary is a 13-year-old student from Visakhapatnam studying in Class 8-A at Little Angels School. He enjoys learning about prehistoric life, evolution, and surprising scientific discoveries, especially when new evidence challenges ideas that scientists once thought were settled.

Imagine stepping outside on a warm afternoon with a snack in your hand when a shadow suddenly sweeps across the ground. You look up and see what appears to be a dragonfly - except its wingspan is nearly as wide as a seagull's. Its enormous eyes scan everything below, its jaws are built for catching prey, and the rapid beating of its wings fills the air with a sound that is impossible to ignore. It sounds like science fiction, but around 300 million years ago, *giant dragonfly-like insects* really did exist. Known as **griffinflies**, these ancient aerial predators could reach wingspans of nearly *70 centimetres*, making them larger than many birds alive today. Although they were not true dragonflies, they looked remarkably similar and occupied a similar role in the ecosystem. For millions of years, they ruled the skies. Then they vanished. *No griffinflies survive today*, and modern dragonflies are only a fraction of their size. For decades, scientists believed they knew exactly why these giants disappeared. However, new research suggests that one of the most popular explanations may not be as solid as once thought.

The traditional explanation focused on oxygen. During the *Carboniferous Period* (about 359 to 299 million years ago), Earth's atmosphere contained significantly more oxygen than it does today. Modern air contains about 21 percent oxygen, but estimates suggest that Carboniferous oxygen levels may have reached between 30 and 35 percent [1]. Scientists reasoned that this would have been especially important for insects because they do not breathe the way humans do. Instead of lungs, insects rely on a network of tubes called tracheae that carry oxygen directly to tissues throughout the body. Since oxygen moves through these tubes by diffusion, many researchers believed that insect size was limited by how efficiently oxygen could travel through their bodies [2]. The more oxygen available in the atmosphere, the easier it would be for insects to support larger bodies. The idea was that larger bodies require more oxygen to sustain their metabolic needs, and with more oxygen in the air, diffusion could supply enough oxygen even to larger insects. As oxygen levels declined over millions of years, insects would have been forced to become smaller because their breathing systems could no longer keep up. This connects to **Kleiber's Law**, which states that an animal's metabolic rate scales with its body mass to the power of 0.75 [4]. In simple terms, larger animals need more energy and oxygen per unit of body mass, so when oxygen levels dropped, insects had to shrink to survive. The idea was simple, logical, and widely accepted. It appeared in scientific literature, documentaries, and museum exhibits and was often treated as an established fact rather than a hypothesis [3].

Recently, however, a team of researchers led by **Edward Snelling** from the *University of Pretoria* in South Africa decided to investigate the issue more closely. Rather than relying on long-standing assumptions, they examined

FIG 1 : *A fossil reconstruction of a giant griffinfly (Meganeurites) from the Palaeozoic era. By André Nel, Jakub Prokop, Martina Pecharová, Michael S. Engel & Romain Garrouste, via Wikimedia Commons, licensed under CC BY 4.0.*

real insects of various sizes and studied their flight muscles using high-resolution electron microscopes. Their attention was focused on tiny structures called **tracheoles**, which are the smallest branches of the insect respiratory system that deliver oxygen directly to muscle cells. If oxygen truly limited insect size, larger insects should have devoted a significant portion of their muscles to oxygen delivery, packing them with vast numbers of tracheoles. This assumption holds true only if we consider that the efficiency of oxygen extraction by tracheoles remains constant across different body sizes. The researchers expected exactly that. Instead, the results shocked them. Even in large insects, tracheoles occupied *less than one percent* of flight-muscle volume. In comparison, the capillaries supplying oxygen to the hearts of birds and mammals occupy roughly ten times more space. When comparing this scaling with Kleiber's Law, the researchers found that the tracheole volume did not increase as rapidly as metabolic rate with body size. In fact, the scaling rate was much slower than predicted, suggesting that insects have plenty of room to deliver oxygen even at larger sizes. The findings suggested that insects may not be struggling to deliver oxygen nearly as much as scientists once believed. Rather than operating at the edge of their respiratory capacity, they appear to have plenty of room to spare. While the study does not completely eliminate oxygen as a factor, it raises serious questions about whether it was truly responsible for the disappearance of giant insects.

If oxygen was not the main reason, then what happened to the griffinflies?

One of the most compelling alternative explanations involves **the rise of birds**. This theory was proposed by scientists studying the evolutionary arms race between predators and prey. During the *Jurassic and Early Cretaceous periods* (about 201 to 100 million years ago), feathered dinosaurs were evolving into increasingly capable fliers, eventually giving rise to the first true birds. These new aerial predators were fast, agile, intelligent, and highly effective hunters. Suddenly, giant insects

FIG 2 : ***Edward Snelling*** *of the University of Pretoria led a study challenging the long-held belief that oxygen limits insect size.*

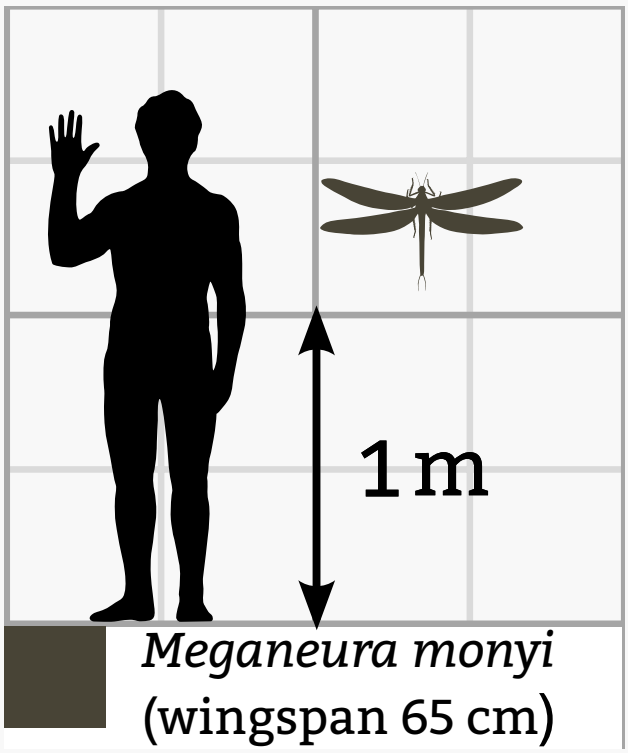

FIG 3 : *Size comparison of the giant griffinfly,* ***Meganeura monyi****, compared to a human. Based on Meganeurites gracilipes from "Palaeozoic giant dragonflies were hawker predators" (André Nel, Jakub Prokop, Martina Pecharová, Michael S. Engel & Romain Garrouste) via Wikimedia Commons, licensed under CC BY 4.0.*

faced a new challenge. Being large may have made them easier to spot and catch. *Try catching a mosquito with your bare hands. Frustrating, isn't it?* Now imagine that mosquito was the size of a pigeon. Suddenly the predator has a much easier job. Scientists refer to this as **size-selective predation**, where predators consistently remove larger individuals from a population, giving smaller ones a better chance of surviving and reproducing [5]. Over millions of years, this evolutionary pressure could have gradually reduced insect size. In a sky increasingly dominated by birds, being enormous may have transformed from an advantage into a serious disadvantage.

Birds may not have been the only factor. Earth's ecosystems were changing dramatically during the *Mesozoic Era* (about 252 to 66 million years ago), a period that followed the age of giant insects. Flying reptiles known as **pterosaurs**, which evolved during the *Late Triassic period* (about 228 million years ago), had already taken to the skies, creating additional competition and predation pressures [7]. Climate conditions shifted repeatedly, habitats changed, and entire ecosystems were transformed. The evolution of flowering plants altered food webs and freshwater environments where dragonfly larvae developed. Large animals often struggle when environmental conditions change rapidly because they require more resources and are generally less adaptable than smaller species. The giant griffinflies may simply have found themselves increasingly unsuited to a changing world. Rather than being driven to extinction by a single cause, they may have been affected by several factors working together over vast stretches of time.

One of the most fascinating implications of the new research is the possibility that giant insects are not biologically impossible today. If oxygen is not the limiting factor scientists once thought it was, then there may be no fundamental reason why insects could not evolve larger sizes under the right conditions. Edward Snelling has suggested that giant insects could potentially reappear in the distant future if environmental conditions were favourable and enough evolutionary time passed. They would not necessarily require an oxygen-rich atmosphere like the one that existed during the Carboniferous Period.

Three hundred million years after giant dragonflies first dominated the skies, scientists are still piecing together exactly why they vanished. Birds, environmental changes, new competitors, and perhaps even oxygen itself may all have played important roles. The full answer remains hidden somewhere in Earth's distant past, waiting to be uncovered by future discoveries. **Yet that uncertainty is what makes the story so fascinating**. The next time a dragonfly darts past you, remember that you are looking at the descendant of a lineage that has survived for hundreds of millions of years through dramatic planetary changes, mass extinctions, and evolutionary revolutions. And perhaps be thankful that its ancient relatives are no longer around, because sharing your lunch with a dragonfly the size of a seagull would be a very different experience indeed.

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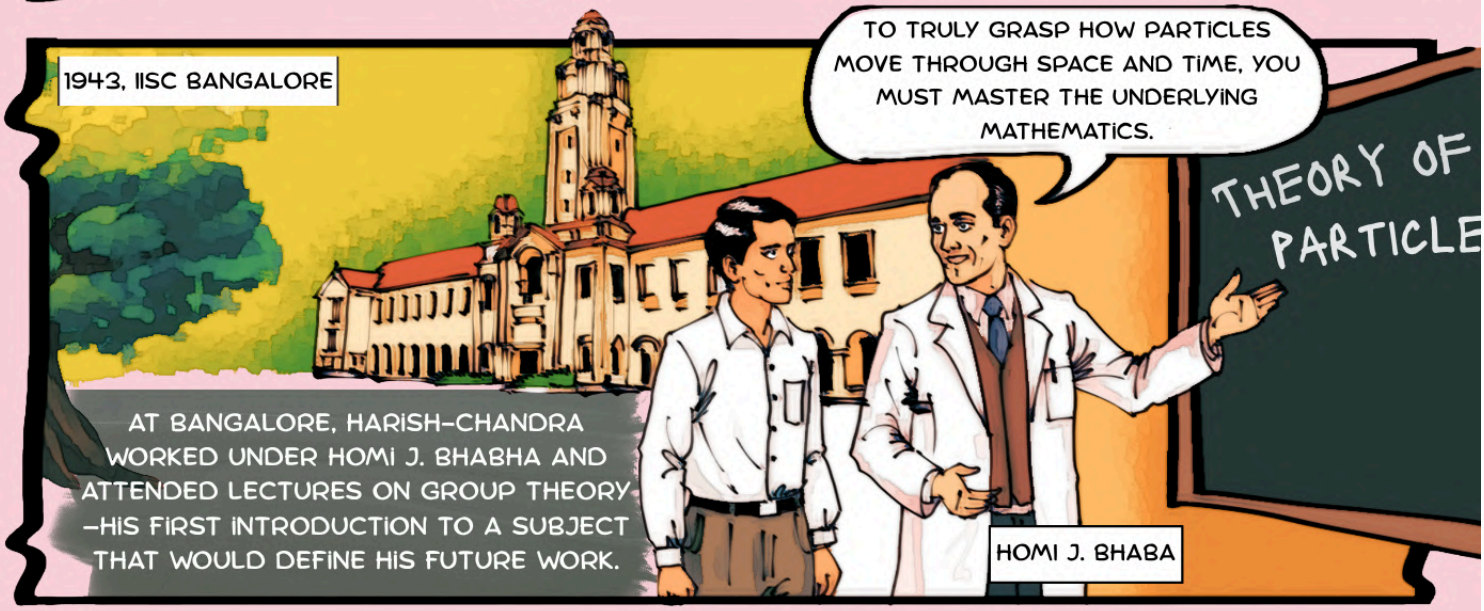
THE PATH TO SYMMETRY

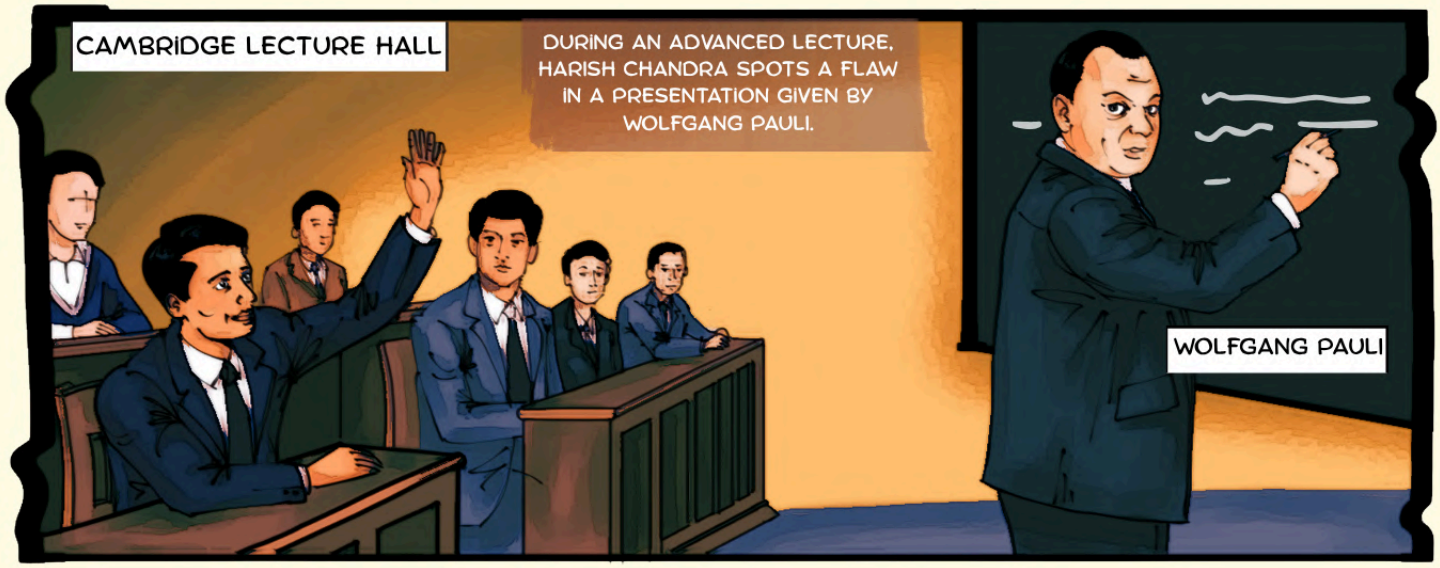
Comic by
ARKADEEP BANDYOPADHYAY

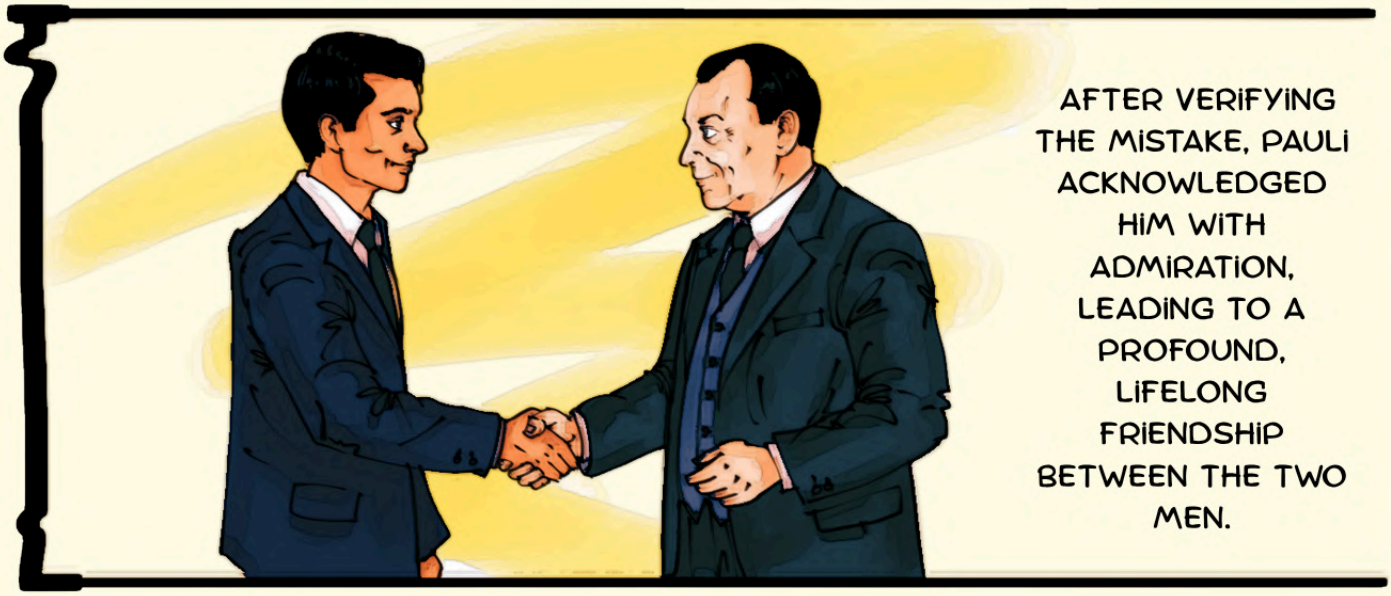

1933, KANPUR, INDIA, YOUNG HARISH CHANDRA
OUTSTANDING ! YOU HAVE PERFECTLY SOLVED THE PHYSICS QUESTION ON THE MRIDANGAM. YOU HAVE BRIGHT FUTURE AHEAD YOUNG MAN !
C.V. RAMAN
HARISH-CHANDRA WAS CONSPICUOUSLY PRECOCIOUS, TEARING THROUGH HIS SCHOOLING YEARS AHEAD OF HIS PEERS. BY 1943, HE FINISHED HIS MASTER'S DEGREE IN PHYSICS WITH A PERFECT SCORE ON A QUESTION ABOUT MRIDANGAM (INDIAN DRUMS) MADE BY THE GREAT INDIAN PHYSICIST C.V. RAMAN


1943, IISC BANGALORE
TO TRULY GRASP HOW PARTICLES MOVE THROUGH SPACE AND TIME, YOU MUST MASTER THE UNDERLYING MATHEMATICS.
THEORY OF PARTICLE
AT BANGALORE, HARISH-CHANDRA WORKED UNDER HOMI J. BHABHA AND ATTENDED LECTURES ON GROUP THEORY –HIS FIRST INTRODUCTION TO A SUBJECT THAT WOULD DEFINE HIS FUTURE WORK.
HOMI J. BHABA


ALGEBRA OF OPERATORS
results on mathematical operators and matrices, and their use in quantum mech
AS HARISH-CHANDRA WAS PURSUING PHYSICS, HE SEEMED TO HAVE DEVELOPED AN INTEREST IN MATHEMATICS AND A RESPECT FOR MATHEMATICIANS.

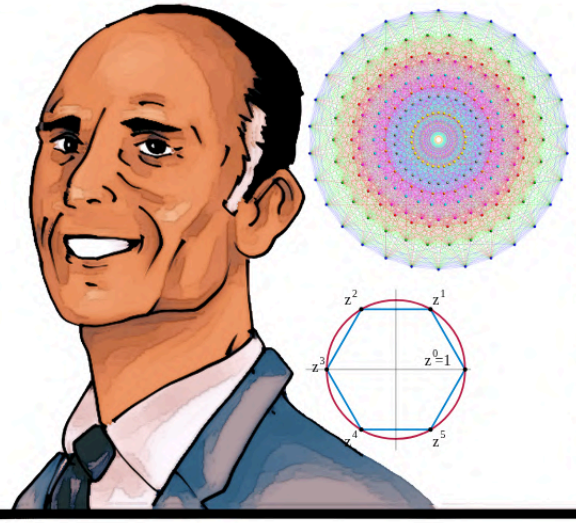

1945, CAMBRIDGE, LONDON
IN 1945, DIRAC HIGHLIGHTED THE IMPORTANCE OF INFINITE-DIMENSIONAL UNITARY REPRESENTATIONS OF THE LORENTZ GROUP. BETWEEN 1945 AND 1947, HARISH-CHANDRA CLASSIFIED THESE REPRESENTATIONS, LAYING THE FOUNDATION FOR HIS LIFELONG CONTRIBUTIONS TO REPRESENTATION THEORY.
HE MOVED TO CAMBRIDGE UNIVERSITY, HAVING BEEN ACCEPTED BY PAUL DIRAC AS A RESEARCH STUDENT.
PAUL DIRAC


CAMBRIDGE LECTURE HALL
DURING AN ADVANCED LECTURE, HARISH CHANDRA SPOTS A FLAW IN A PRESENTATION GIVEN BY WOLFGANG PAULI.
WOLFGANG PAULI


AFTER VERIFYING THE MISTAKE, PAULI ACKNOWLEDGED HIM WITH ADMIRATION, LEADING TO A PROFOUND, LIFELONG FRIENDSHIP BETWEEN THE TWO MEN.

1947, PRINCETON UNIVERSITY

AFTER MOVING TO PRINCETON IN 1947, HARISH-CHANDRA GRADUALLY LEFT PHYSICS TO PURSUE MATHEMATICS FULL-TIME. INSPIRED BY CLAUDE CHEVALLEY, HE FOCUSED ON LIE GROUPS AND LIE ALGEBRAS, ESPECIALLY THE REPRESENTATION THEORY OF SEMISIMPLE LIE GROUPS, LAYING THE FOUNDATION FOR A FIELD HE WOULD TRANSFORM.



HARISH-CHANDRA'S PIONEERING WORK ESTABLISHED MANY OF THE FUNDAMENTAL METHODS OF MODERN REPRESENTATION THEORY. IN RECOGNITION OF HIS CONTRIBUTIONS, HE WAS ELECTED A FELLOW OF THE ROYAL SOCIETY (1973), RECEIVED THE SRINIVASA RAMANUJAN MEDAL (1974), WAS ELECTED TO THE INDIAN NATIONAL SCIENCE ACADEMY AND THE INDIAN ACADEMY OF SCIENCES (1975), AND LATER BECAME A MEMBER OF THE U.S. NATIONAL ACADEMY OF SCIENCES (1981).

HARISH-CHANDRA'S LEGACY LIVES ON THROUGH THE PROFOUND IMPACT OF HIS WORK ON MODERN MATHEMATICS AND THEORETICAL PHYSICS. TODAY, THE HARISH-CHANDRA RESEARCH INSTITUTE (HRI) IN PRAYAGRAJ BEARS HIS NAME, HONORING ONE OF INDIA'S GREATEST MATHEMATICIANS. HIS GROUNDBREAKING IDEAS CONTINUE TO SHAPE REPRESENTATION THEORY, INSPIRING GENERATIONS OF MATHEMATICIANS IN INDIA AND AROUND THE WORLD.

HRI , ALLAHABAD

Hi! I'm **Arkadeep Bandyopadhyay**, a BS-MS student at IISER Kolkata, aspiring to major in chemistry. Alongside science, I have a deep passion for design and visual art. I enjoy exploring different artistic mediums and styles as a way to learn and grow creatively. My interest in comics and graphic novels has shaped my appreciation for visual storytelling, and I enjoy blending creativity with curiosity through my work.

Insight Digest – Curated Science News

Fresh highlights from the frontiers of science

Swarnendu Saha From Instability to Saturation: Tracking the Thermodynamic Life Cycle of Tropical Mesoscale Convective Systems

Abhirup Mukherjee Dynamics of Superconducting Pairs in the Two-Dimensional Hubbard Model

Shriparna Chattopadhyay Can our brain predict our next friend?

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

From Instability to Saturation: Tracking the Thermodynamic Life Cycle of Tropical Mesoscale Convective Systems

Kafy, A.A., Ibrahim, W.M., Baky, A.A. et al. Sci Rep 16, 6827 (2026))

Contributed by **Swarnendu Saha (IIT BOMBAY)**

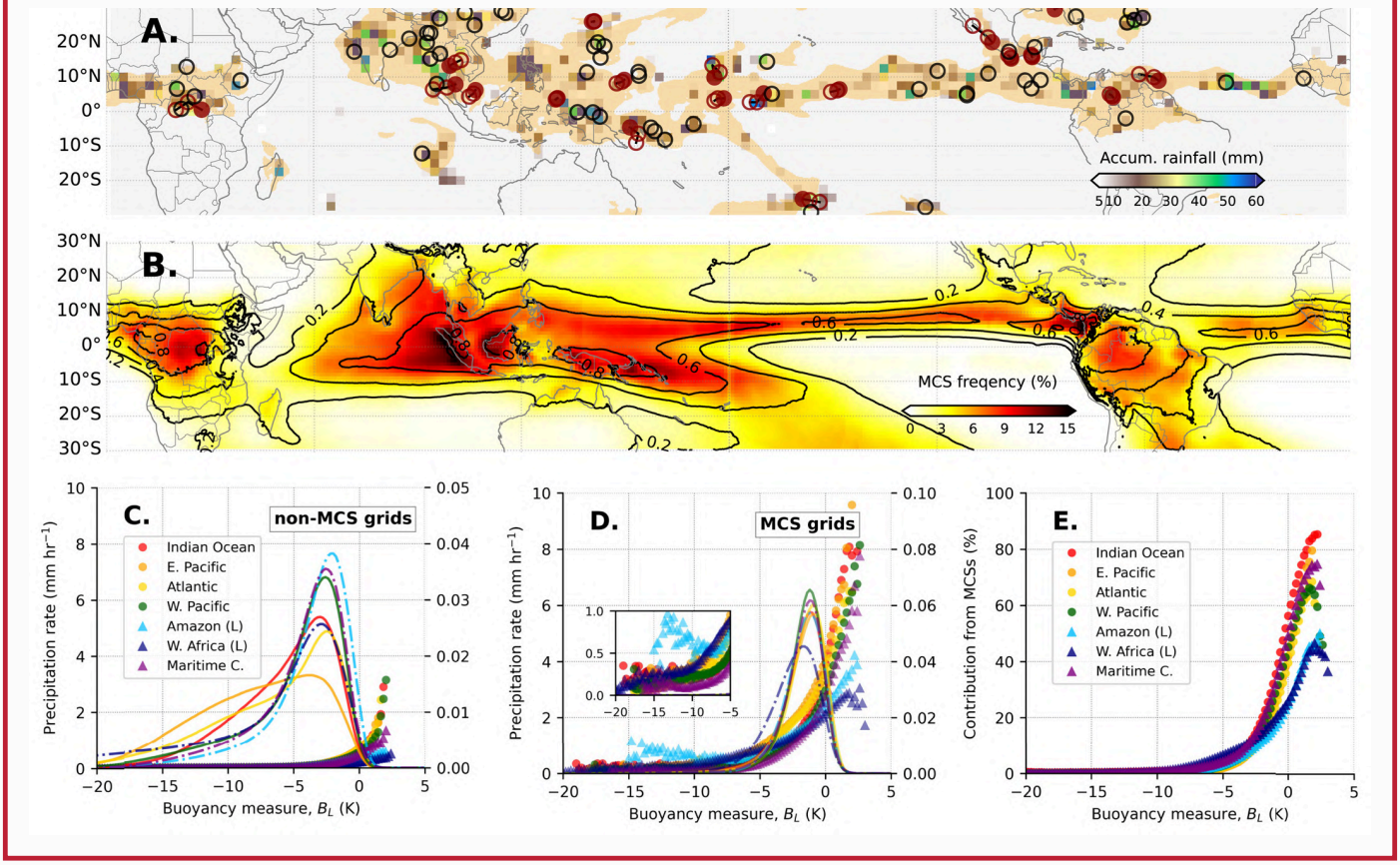
Subjects: mesoscale systems, lagrangian framework, precipitation

Mesoscale convective systems (MCSs)—large, organized clusters of thunderstorms that can span hundreds of kilometers and persist for many hours—generate roughly half of all tropical rainfall. Despite their outsized climatic importance, MCSs are poorly represented in global climate models and are often misrepresented even in convection-permitting simulations. A major reason is that we lack clear observational benchmarks for how the thermodynamic environment surrounding an MCS evolves as the system moves through its life cycle, from birth to decay.

This study addresses that gap by combining two datasets: a 20-year, satellite-derived global MCS tracking database (PyFLEXTRKR, using GPM IMERG precipitation and infrared brightness temperature) and hourly ERA5 reanalysis fields. Nearly 100,000 tropical MCS tracks (56,605 oceanic, 42,549 continental) were analyzed. The key diagnostic tool is an empirical lower-tropospheric buoyancy measure, B_L, previously developed to link convective instability to precipitation in an Eulerian (fixed-location) framework. Here it's applied for the first time in a Lagrangian sense—following individual MCSs through time.

The central finding is that MCS frequency and precipitation intensity are tightly linked to periods when B_L exceeds roughly −5 K, a threshold that also marks where non-MCS convection begins to substantially deepen—suggesting this value marks a general transition into deep, organized convection. More importantly, the two B_L components trace distinct, physically interpretable trajectories across the life cycle. Initiation is characterized by high undilute instability combined with moderate subsaturation—conditions favorable for triggering but not yet fully moistened. As MCSs mature, instability actually decreases, but the environment becomes nearly saturated, sustaining strong precipitation through a different mechanism—one likely tied to boundary-layer cooling from evaporating stratiform rain rather than fresh convective instability. By the decay and termination stages, the environment becomes both stable and strongly subsaturated, effectively shutting down further convective development.

This life-cycle-dependent decoupling between instability and moisture has an important implication: B_L alone, without knowing the life-cycle stage, is not a fully sufficient predictor of MCS behavior—precipitation and buoyancy relationships depend on convective memory (the recent history of the system), not just the instantaneous environment. The associated vertical velocity fields (from ERA5) and cold-cloud fractions support this interpretation, showing consistent low-level ascent that weakens as systems decay.



Dynamics of Superconducting Pairs in the Two-Dimensional Hubbard Model

G. Sordi, E. M. O'Callaghan, C. Walsh, M. Charlebois, P. Sémon, and A.-M. S. Tremblay. Phys. Rev. Lett. 136, 256503. June 2026)

Contributed by **Abhirup Mukherjee (DPS, IISER Kolkata)**

Subjects: twisted bilayer graphene, superconductivity, strong-correlations

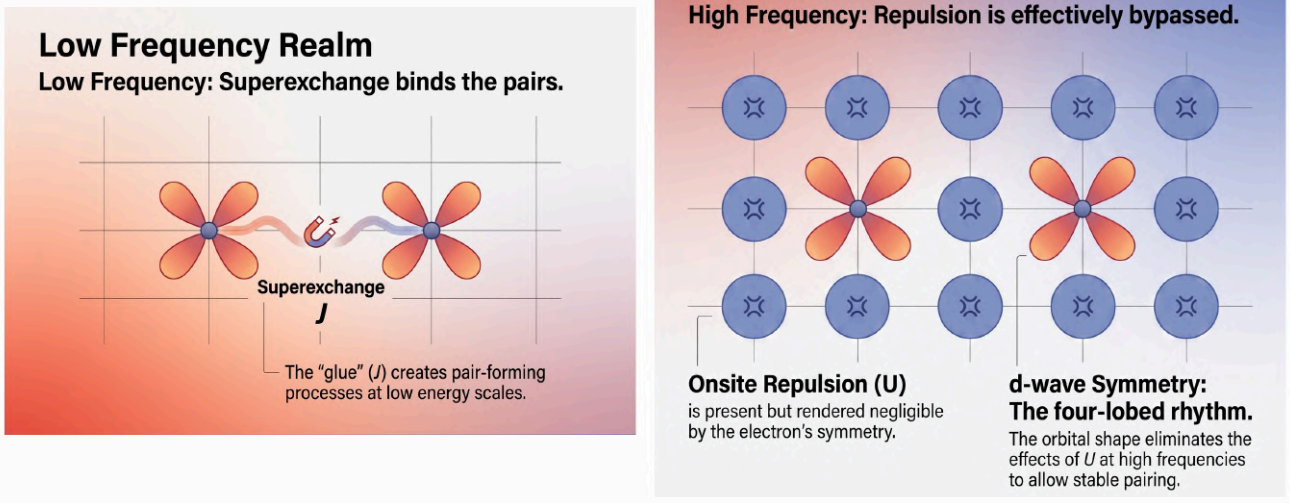
This work investigates the specific time and energy scales that allow electrons to form superconducting pairs within the two-dimensional Hubbard model. Specifically, it seeks to identify which processes acting at which energy scales play the role of the "glue" that binds electrons together to bring about superconductivity.

For several decades, the mystery of high-temperature superconductivity – the ability of certain normally insulating materials to conduct electricity without any energy loss at relatively higher temperatures – has remained one of the most significant challenges in modern physics. It is accepted that superconductivity requires electrons to form tightly bound states called *Cooper pairs*; **however, it is not clear how materials with strong Coulomb repulsion between electrons, such as the high-T_c cuprates that show high temperature superconductivity, will lead to such attractive pairs**. In particular, we still lack a fundamental understanding of the electron dynamics, or the "timing" of their interactions that form the *pairing mechanism*.

In the past, theoretical approaches have struggled to reconcile the different and often conflicting timescales at play: some interactions happen nearly instantaneously, while others occur much more slowly. **This is particularly challenging because multiple energy scales and timescales have to be treated on an equal footing, meaning methods that make adhoc assumptions and approximations will not work**. This work studies these questions on the 2D Hubbard model – a model of electrons that can move around on a lattice as well as feel the Columb repulsion of other electrons if they happen to appear on the same site.

The work reveals that superconducting pairing is almost entirely a low-frequency, long-lived process driven by "superexchange" interactions. This is an effective tendency that is mediated by the electronic Columb repulsion in the presence of the kinetic energy. Because the repulsion favours each site to have a single electron, two nearest-neighbour sites must have opposite spins, otherwise an electron cannot move from one site to the other (owing to Pauli's exclusion principle). This leads to an emergent effect where a pair of adjacent sites lower their energy by making the electrons spin antiparallel, and it is this binding effect that leads to the pairing.

The work also found that high-frequency electronic repulsion—which usually breaks pairs—is effectively bypassed by the *d*-wave symmetry of the electrons. The *d*-wave symmetry refers to the fact that the 2D square lattice structure causes the two electron wavefunction to vanish when they occupy the same site. Ultimately, therefore, the net contribution to superconductivity comes solely from the previously mentioned slower processes, confirming that the "glue" of the system operates on a very specific, manageable timescale.



In the complex landscape of the 2D Hubbard model, electrons overcome their natural repulsion by finding a specific temporal "sweet spot". While intense, high-frequency repulsion (U) would typically break electron pairs apart, their unique d-wave symmetry—visualized here as four-lobed orbits—allows them to physically sidestep these collisions. This leaves a clear path for a slower, low-energy interaction called superexchange (J) to act as the "glue" that binds them together. By demonstrating that superconductivity is sustained entirely by these long-lived, low-frequency processes, this research provides a vital roadmap for next-generation experiments aiming to capture the fundamental mechanism of high-temperature superconductors. ***Generated using NotebookLM.***

Can our brain predict our next friend?

Shen, Y.L., Hyon, R., Wheatley, T. et al. Neural similarity predicts whether strangers become friends. Nat Hum Behav 9, 2285–2298 (2025))

Contributed by **Shriparna Chattopadhyay (Research Scholar, DBS, IISER Kolkata)**

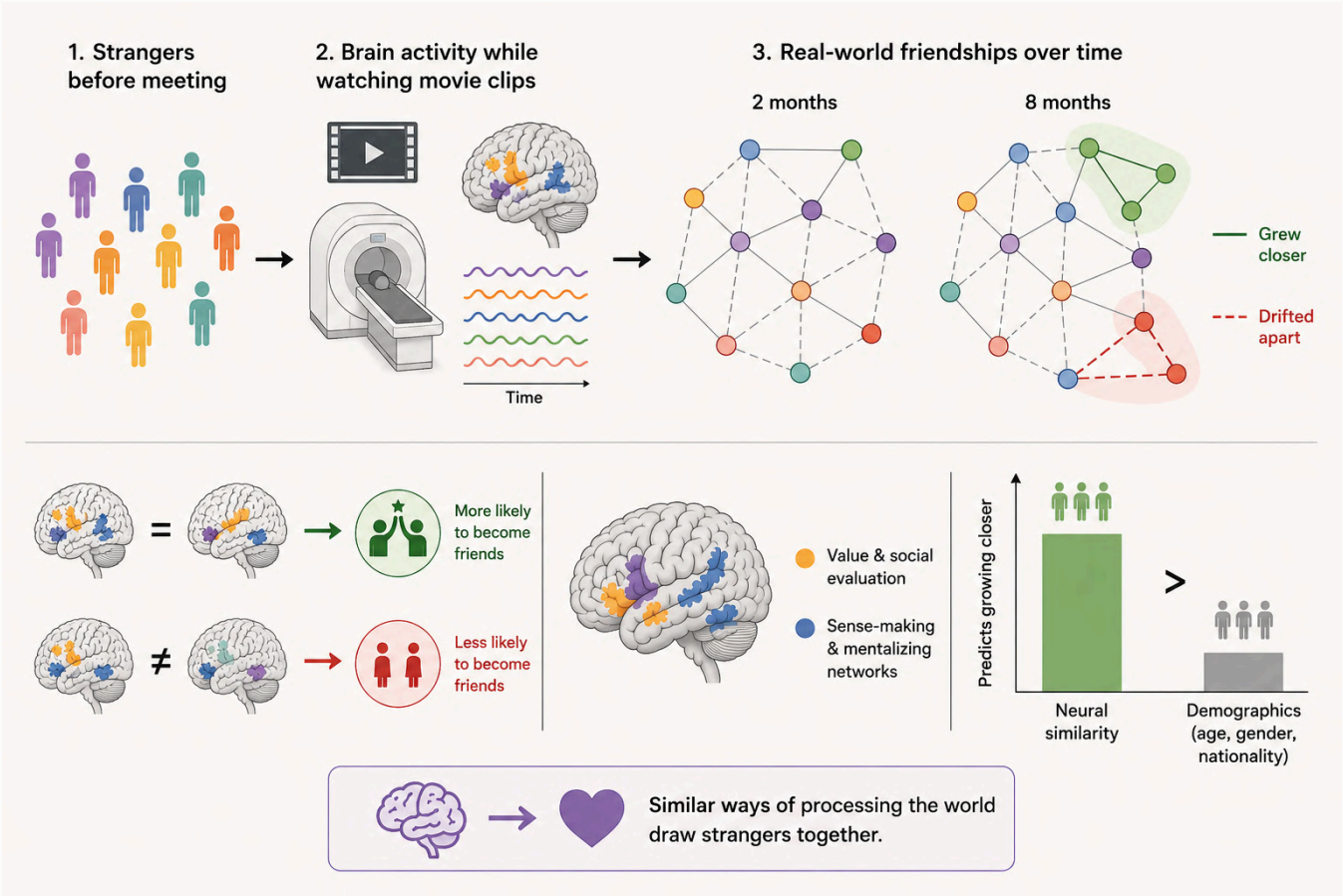
Subjects: fmri, neural homophily, social neuroscience, default mode network, frontoparietal control network

Ever pondered: why do we instantly vibe with some people while others remain strangers?

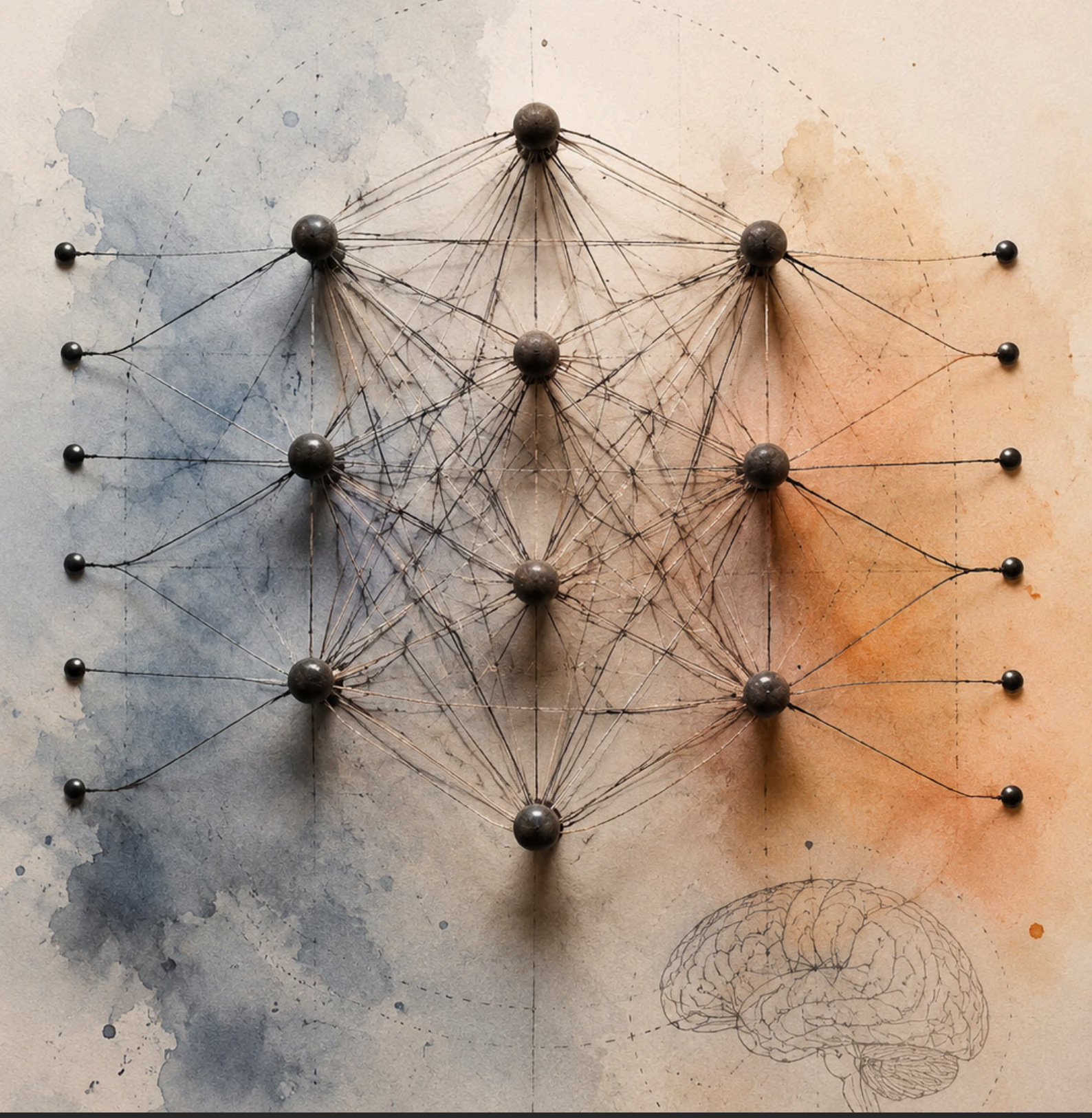
Well! A new study published in Nature Human Behaviour shows that a part of the answer lies in 'how our brain processes the world!' This new longitudinal study claims that our brain might predict 'who will be your next friend' even without meeting them.

Researchers carried out fMRI on 41 incoming graduate students on their arrival in the campus even before they had a chance to interact or meet each other. While undergoing fMRI, participants were shown a series of short movie clips of different genres (like documentary, comedy, debate) spanning different topics (such as food, science, sports, environment and social events). The results seem quite interesting: pairs of participants whose brains had responded to the videos in similar ways as total strangers were significantly more likely to become close friends over time (8 months were considered as the span) or in the other way the neural patterns were especially strong among pairs of participants who grew closer during the study. This wasn't just about liking the same show/ movie clip, the effect held up after accounting for shared demographics like age, nationality, and gender. Researchers show that the participants who became friends in the eight-month mark showed higher initial similarity in the left orbitofrontal cortex of our brain,also neural similarity across 40 different brain regions predicted which pairs of participants would grow closer over time. The regions included the Default Mode Network (DMN) and Frontoparietal Control Network (FPCN), which are involved in "sense-making," mentalizing, and interpreting complex social narratives.

This study concludes by saying that while friendships may begin by chance, long-term compatibility is shaped by pre-existing similarities in how people perceive, interpret and respond to the world. Finally the study introduces the term- neural homophily, suggesting that we are naturally captivated by those who "see the world" the same way we do.



fMRI on participants were carried while showing them movie clips. Participants with more similar neural responses, particularly across the DMN and FPCN, were more likely to become closer friends over the following eight months than those with less similar brain activity.



Science Games

Science Quiz Guess Which Scientific-Sounding Statement Is A Myth

Themed Crossword This issue's crossword is inspired by the intersection of artificial intelligence and science.

Who Am I? Can you identify these landmark popular science books from just a few clues?

Linked List Name all the animals to complete the chain.

3 Truths, 1 Lie: Science Quiz

Guess Which Scientific-Sounding Statement Is A Myth

Abhirup Mukherjee *[DPS, IISER Kolkata]*

Q1. Which of the following is a myth?
I. Lightning can strike the same place more than once.
II. The Great Wall of China is visible from the Moon with the naked eye.
III. Sharks existed before trees.
IV. A day on Venus is longer than its year.

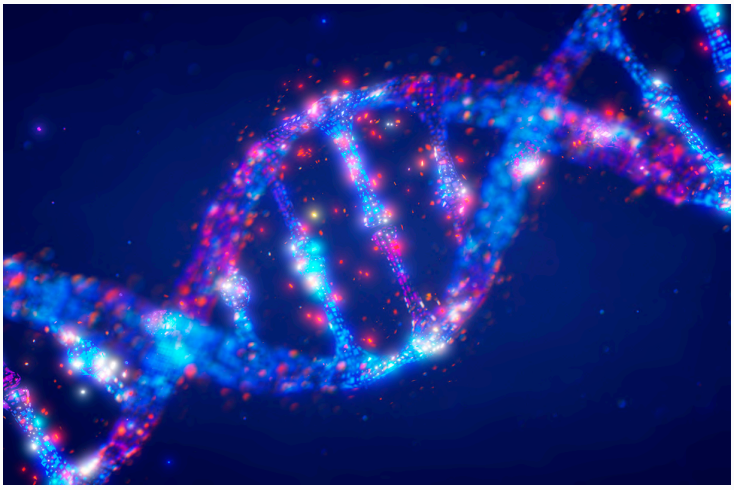
Q2. Which of the following is a myth?
I. Your fingernails continue growing after death.
II. Some fungi can turn ants into 'zombies'.
III. There are lakes beneath Antarctica's ice.
IV. Water can boil at room temperature.

Q3. Which of the following is a myth?
I. Bananas are naturally slightly radioactive.
II. Honey can remain edible for thousands of years.
III. Goldfish have a memory of only three seconds.
IV. Octopuses have three hearts.

Q4. Which of the following is a myth?
I. The human body contains enough carbon to make thousands of pencil leads.
II. Glass is actually a liquid that flows over time.
III. The Eiffel Tower becomes taller in summer.
IV. A teaspoon of neutron star matter would weigh billions of tonnes.

Q5. Which of the following is a myth?
I. There are more possible chess games than atoms in the observable universe.
II. Some turtles can breathe through their rear ends.
III. Camels store water in their humps.
IV. Saturn would float in a sufficiently large ocean.

Q6. Which of the following is a myth?
I. Wombat droppings are cube-shaped.
II. The Moon is slowly moving away from Earth.
III. Bulls become angry when they see the colour red.
IV. Some metals can 'remember' their original shape.



Q7. Which of the following is a myth?
I. Hot water can sometimes freeze faster than cold water.
II. Humans share about half of their DNA with bananas.
III. A bolt of lightning is hotter than the surface of the Sun.
IV. Humans only use 10% of their brains.

Q8. Which of the following is a myth?
I. A cloud can weigh hundreds of tonnes.
II. The Coriolis effect determines the direction water drains in household sinks.
III. The International Space Station experiences about 16 sunrises each day.
IV. A blue whale's heart can weigh as much as a small car.

Q9. Which of the following is a myth?
I. The Sahara Desert was once much greener than it is today.
II. Diamonds are formed from compressed coal.
III. A day on Mercury lasts longer than its year.
IV. The fingerprints of koalas resemble those of humans.

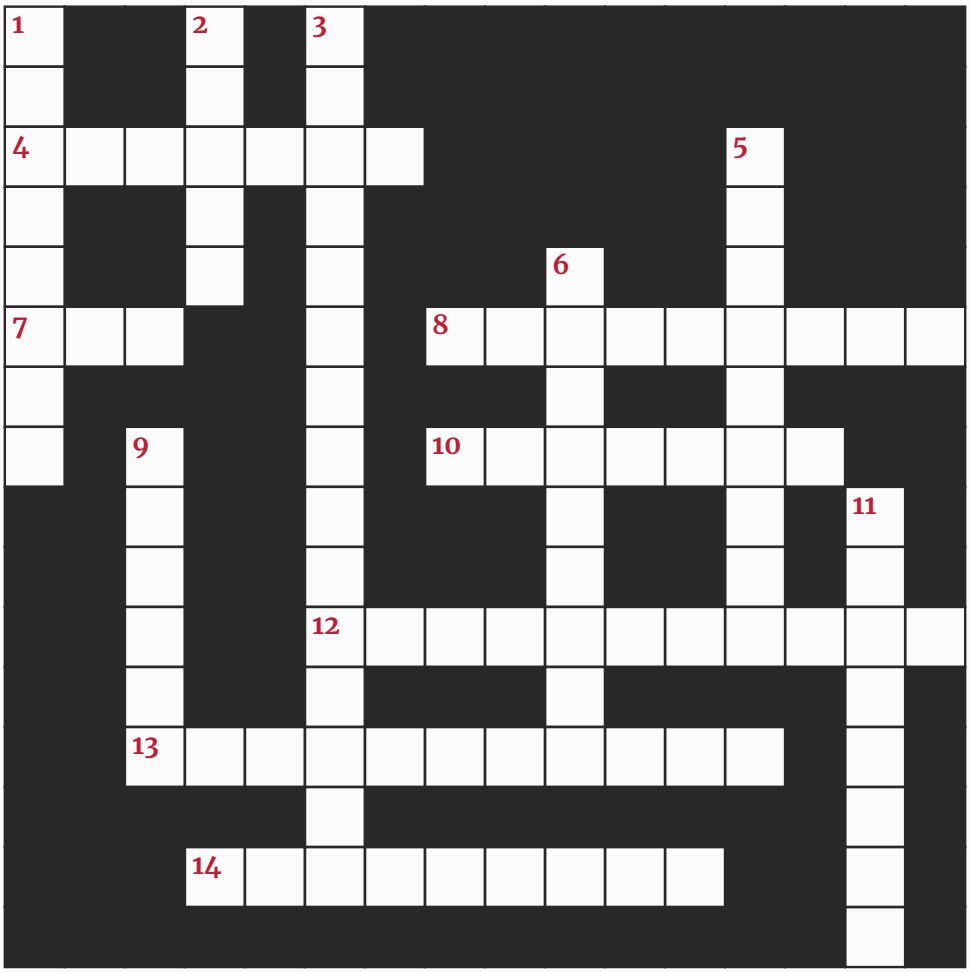
Q10. Which of the following is a myth?
I. There are more trees on Earth than stars in the Milky Way.
II. An ostrich buries its head in the sand when frightened.
III. Jellyfish have existed longer than dinosaurs.
IV. Some bacteria can survive in nuclear reactors.

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

Themed Crossword – AI and Science

This issue's crossword is inspired by the intersection of artificial intelligence and science.

***Abhirup Mukherjee** [DPS, IISER Kolkata]*



Across

4. Python-based open-source deep learning framework developed by Meta AI (7)
7. Generative AI model developed at the Arc Institute and NVIDIA to predict genetic mutations and design entire synthetic genomes from scratch (3)
8. AI that folded proteins before your laundry (9)
10. Artificial intelligence-based weather forecasting model developed by Google DeepMind that predicts global weather and extreme conditions up to 15 days in advance (7)
12. DeepMind AI that discovered faster matrix multiplication algorithms than those designed by humans (11)
13. Open-source, generative AI tool developed by the Institute for Protein Design to create custom protein structures (11)
14. AI system that discovers new, human-interpretable computer programs for solving mathematical and algorithmic problems (9)

Down

1. Recurrent neural network developed in the 1980s based on energy minimization that implements associative memory (8)
2. AI that utilizes deep learning to predict 2.2 million novel crystalline materials (5)
3. Algorithm popularized by Geoffrey Hinton for training neural networks (15)
5. Generative AI technique that creates images or other data by gradually reversing a noise-adding process. (9)
6. Disordered magnetic systems whose energy landscape inspired Hopfield networks and modern ideas in neural computation. (9)
9. Computational biologist behind AlphaFold's breakthrough, Co-recipient of the 2024 Nobel Prize in Chemistry (last name) (6)
11. Deep learning model developed by NASA to discover and validate exoplanets from space telescope data. (8)

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

Who Am I? Name These Iconic Books

Can you identify these landmark popular science books from just a few clues?

***Abhirup Mukherjee** [DPS, IISER Kolkata]*

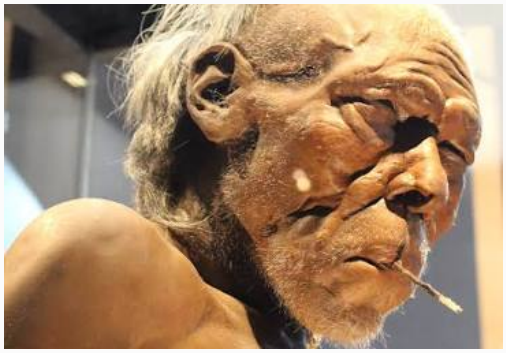
Can you identify these landmark popular science books from just a few clues?

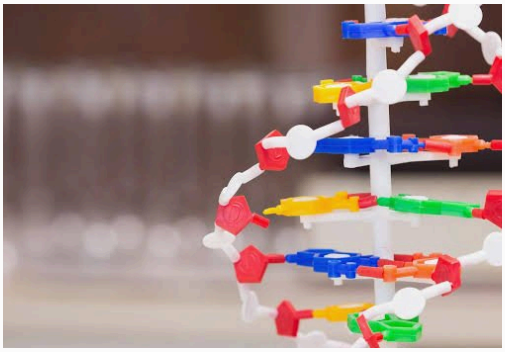
Which popular science book am I?

- I explain how tiny changes accumulate over immense spans of time.
- My ideas transformed biology and our understanding of life's diversity.
- I was published in 1859 and sparked one of the greatest scientific debates in history.
- My central mechanism is natural selection.

Which popular science book am I?

- I explore humanity's journey from prehistoric hunter-gatherers to the modern world.
- My chapters revolve around three major revolutions that shaped civilization.
- I became an international bestseller despite being written by a historian rather than a scientist.
- My title is just one word.





Which popular science book am I?

- I reveal the hidden lives of genes and the history of heredity.
- My author won the Pulitzer Prize for another book on cancer.
- My subtitle is "An Intimate History".
- My title describes the unit of heredity itself.

Which popular science book am I?

- I take readers on a journey from the Big Bang to the origins of life.
- My author later became one of television's most beloved science communicators.
- My opening sentence begins, "The cosmos is all that is or ever was or ever will be."
- I share my name with a famous television series.

Linked List – All About Animals

Name all the animals to complete the chain.

***Abhirup Mukherjee** [DPS, IISER Kolkata]*

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: **ANTEATER**

1. The largest species of kangaroo. (**12**)

R											

2. A large, flightless bird native to Africa. (**7**)

3. Large, semi-aquatic mammal whose name is derived from the Ancient Greek word for 'river horse' (**12**)

4. Ocean creature famous for the fact that the males, rather than the females, carry and give birth to the babies (**9**)

5. A small African mammal famous for its long trunk-like nose despite not being an elephant. (**14**)

6. Native Australian animal that uses its incredibly tough, cartilaginous rear end to block predators from entering its underground burrows (**6**)

7. Bird that's native to the rainforests of Central and South America, and has a large, lightweight beak made of keratin (**6**)

8. Largest antelope species in Asia, its Hindi name literally translates to 'blue cow' (**6**)

9. Large, mostly herbivorous, tree-dwelling lizard native to tropical areas of Central and South America, known for the crest of spines along its back and its long whip-like tail (**6**)

					A

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

Academic Listings: Internships, PhDs, Post-docs

Position titles are hyperlinked

POSTDOCTORAL AND OTHER POSITIONS

Assistant Professor, Department of Earth System Science, Stanford Doerr School of Sustainability	⏰ **Deadline**: August 4 2026
Research Position in High Energy Astrophysics	⏰ **Deadline**: August 10, 2026
Research Engineer or Postdoctoral Researcher	⏰ **Deadline**: 9 August 2026
Tenure-track faculty position in Geology/Geomorphology	⏰ **Deadline**: Jul 31, 2026
Assistant/Associate Professor (F3/F4) Outer Solar System Science & Space Grant Associate Director	⏰ **Deadline**: Aug 25, 2026
Assistant Professor, Department of Earth System Science, Stanford Doerr School of Sustainability	⏰ **Deadline**: Aug 4, 2026
Assistant Professor, Analytical Lab Manager- The university of Hawaii	⏰ **Deadline**: Aug 12, 2026
Postdoctoral Research Scholar- The university of south florida	⏰ **Deadline**: Aug 7, 2026

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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*.

Science Articles

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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.

The Last Page

Crossword

Across

4. PYTORCH
7. EVO
8. ALPHAFOLD
10. GENCAST
12. ALPHATENSOR
13. RFDIFFUSION
14. FUNSEARCH

Down

1. HOPFIELD
2. GNOME
3. BACKPROPAGATION
5. DIFFUSION
6. SPINGLASS
9. JUMPER
11. EXOMINER

Quiz

1. The Great Wall of China is visible from the Moon with the naked eye.
2. Your fingernails continue growing after death.
3. Goldfish have a memory of only three seconds.
4. Glass is actually a liquid that flows over time.
5. Camels store water in their humps.
6. Bulls become angry when they see the colour red.
7. Humans only use 10% of their brains.
8. The Coriolis effect determines the direction water drains in household sinks.
9. Diamonds are formed from compressed coal.
10. An ostrich buries its head in the sand when frightened.

Linked List

1. RED KANGAROO
2. OSTRICH
3. HIPPOPOTAMUS
4. SEA HORSE
5. ELEPHANT SHREW
6. WOMBAT
7. TOUCAN
8. NILGAI
9. IGUANA

Who Am I?

1. On the Origin of Species
2. Sapiens
3. The Gene
4. Cosmos

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

To The Top

All 5 Indian students win GOLD at the 56th International Physics Olympiad (IPhO) 2026 in Bucaramanga, Colombia. Prof. Ananda Dasgupta (extreme right) was one of the two scientific observers. He helped with the training and selection in the Orientation Cum Selection Camp, and also helped in training the final team in their pre-departure camp.
Credit: IISER Kolkata

All About Yoga

Institute celebrated the 12th International Day of Yoga on June 21. This year's theme, "Yoga for Healthy Ageing," highlights the importance of yoga in promoting lifelong health, fitness and mental well-being. *Credit: IISER Kolkata*

Giving It Back

The Institute celebrated its 21st Foundation Day on 10th July. This occasion was observed as an Open Day, welcoming about 1,000 students and teachers from nearby schools.
Credit: IISER Kolkata