January, 2025 Issue 01

THE CANONICAL

THE INTER IISER-IISC PHYSICS MAGAZINE

THE CANONICAL

CONTRIBUTORS

ENSEMBLE

Indian Institute of Science
Bengaluru

ensemble.iisc.ac.in

ensemble.iisc@gmail.com

@ensemble8887

ensemble.iisc

137 INVERSE

Indian Institute of Science
Education and Research
Behrampur

sites.google.com/iiserbpr.ac.in/137-inverse/home

phy_club@iiserbpr.ac.in

@137inverse

137inverse

@137Inverse

PHI@I

Indian Institute of Science
Education and Research
Mohali

phiclubiiserm.github.io

phiclub@iisermohali.ac.in

@phiiserm

@physicsclubiiserm

@phyclub_iiserm

PHYSICSCLUB

Indian Institute of Science
Education and Research
Bhopal

phyclub-iiserb.netlify.app

iiserbhopalphyclub@gmail.com

@physicsclubiiserb5203

@phyclub_iiserb

GLUON

Indian Institute of Science
Education and Research
Kolkata

dps.journalclub@iiserkol.ac.in

THE CANONICAL

MEET THE TEAM

Sheersh Sen
ENSEMBLE
Editing, Designing

Adityadhar Dwivedi
PHI@I
Editing, Designing

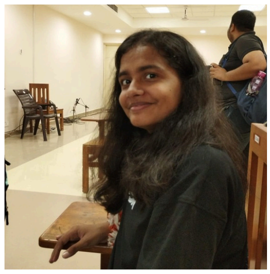
Atreyee Barman
137 INVERSE
Designing

Medha Roy Choudhury
GLUON
Editing

Arpit Chhabra
PHI@I
Editing, Designing

Aditi Sahu
137 INVERSE
Editing

Krishna Aasrith
IBPC
Editing, Designing



Prachiti Sharma
137 Inverse
Editing

Aditi Mishra
IBPC
Designing,
Cover Page Design

We are extremely grateful to all esteemed Professors who gave us insightful interviews. The magazine further owes its existence to everyone who put in the effort to create awesome articles and pieces. We're very grateful.

A note from *the Editors*

Through the miracle we commonly know as an internship, a representative of Ensemble happened to meet a representative of 137 Inverse. The topic of the ensuing conversation was, vaguely, 'what can we even do with our clubs?'

A collaboration was certainly on the cards. But it is difficult to collaborate. It's especially difficult when the collaboration involves writing and designing a magazine for a physics club that will probably reach a sizeable audience, but won't guarantee interaction. But it was worth a shot. So we took one.

After reaching out to friends of friends of friends, we got some people onboard from across India. And that's it folks, we have the Canonical! It is a conglomerate of varying styles and philosophies, not entirely different from how all of us are. But it is also a magazine that 'exists', as opposed to the all-probable non-existence. We believe that's a significant thing.

2024 was when work on the Canonical began, keeping in mind that 2025 was proclaimed to be the International Year of Quantum Science and Technology. That's somewhat our theme, if such a thing exists. We've got technical articles, informal pieces and wonderful interviews with some brilliant scientists from our institutes. We hope you enjoy it. And, at the end of it, learn just one more new thing.

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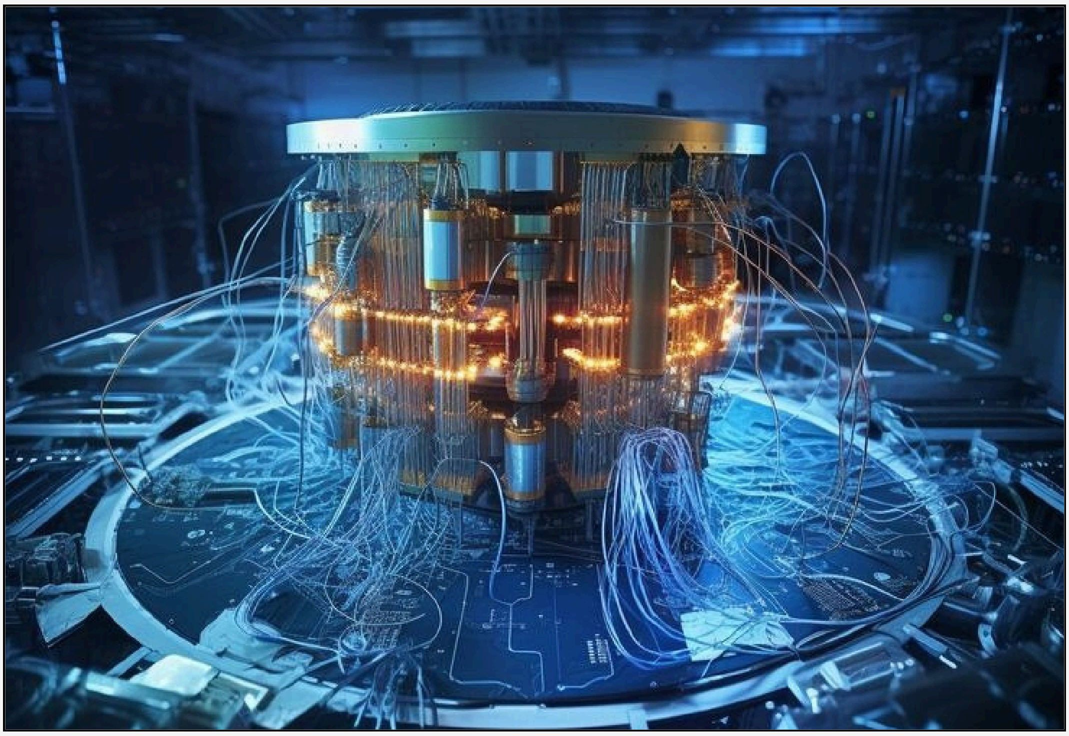
QUANTUM TECHNOLOGY AND INFINITE POSSIBILITIES

By
Samrat Dey,
IBPC



Quantum technology is reshaping the limits of innovation, unlocking possibilities once thought to belong to science fiction. From lightning-fast computations to unbreakable encryption, it's redefining industries and charting a bold path into the future.

Introduction

The early 20th century saw the emergence of a new kind of physics that challenged the very foundations of our beliefs about the universe: Quantum Mechanics. It describes the behaviour of matter at the smallest scales, presenting principles that defy common sense. Even so, this theory has survived the trial of experiments coming its way and is now an established and accepted science. Much like the later half of the 19th century saw the development of the science of electromagnetism and its applications slowly making their way into technology, the 20th century was reserved for the rise of quantum mechanics and its subsequent adoption into modern technology. Today we stand on the brink of a new era – one where the wonders of the quantum world are not just limited to theoretical physics and science fiction but are being harnessed in groundbreaking technologies that could reshape our future. Quantum technology, once the stuff of comic books, is now expected to revolutionise fields like computing, sensing, communication and potentially many others!

In this article, we will explore some state-of-the-art quantum technology: learning about the rudimentary science behind the scenes and its potential for the future. From unbreakable encryption to ultra-fast computing, quantum technology offers novel ways to challenge the limitations imposed by classical machines till now, making the impossible seem possible. But as with any great leap forward, it also comes with challenges and questions that society must grapple with. Let's embark on this journey into the quantum realm, where the future is being forged at the smallest of scales!

QUANTUM SENSORS: DETECTING THE UNDETECTABLE

A sensor is a measuring device used to sense changes in some physical property of the surrounding environment, e.g. pressure, temperature, load etc. They are often manufactured into larger systems and devices and can monitor different variables depending on their type. But there is a limit to how precisely traditional sensors can measure things. Modern applications of technology are in dire need of more sensitive equipment. This is where Quantum Sensors step in.

Quantum sensors are ultra-sensitive devices designed to measure things at an unprecedented level of detail by using the wondrous laws of quantum mechanics. These sensors can detect tiny variations in various physical properties, including time, magnetic fields and gravitational forces, far beyond the capabilities of classical sensors. There is another advantage to them: these sensors rely on the constants of nature for measurement; therefore, they are self-calibrating and their measurements don't drift off over time like those of traditional sensors. Let's check out some awesome examples of quantum sensors.

Quantum Clocks

Quantum Clocks are among the most developed quantum sensors. They use single ions that are laser-cooled in an electromagnetic ion trap. Time is measured using ion vibrations, powered by an ultraviolet (UV) laser. For example, the NIST-F1 Cesium atomic clock is expected to be accurate to 1 second over 100 million years. That's good, but a quantum clock is better. It is accurate to 1 second over 3+ billion years.

Quantum Clocks are also used to increase the accuracy of other sensors. Precise timing is used for a sensor technique called 'super-resolution', where multiple sequential sensor measurements are taken with precise time markers. Software is then employed to combine these measurements and achieve higher levels of resolution.

Quantum Gravimeters

Like Quantum Clocks, Quantum Gravimeters are already in widespread use, e.g., by scientists, surveyors, and civil engineers. A common method is atom interferometry, which uses atoms cooled to near absolute zero and placed in a free fall. For example, one gravitometer design uses laser-cooled rubidium atoms. It relies on the wave-particle duality and quantum matter-wave interferences to measure the acceleration of the rubidium atoms as they fall. The instrument can track variations in the value of gravity over time.

Quantum Magnetometers

Quantum Magnetometers use the spin of subatomic particles like nuclei or unpaired valence electrons. They provide high sensitivity and are used for various applications from geological measurements to brain imaging. They use a type of polarisation where particles are caused to precess in an ambient magnetic field. The frequency of the precession can be translated into magnetic field measurements.

Imaging

Quantum imaging sensors are being developed for use in magnetic resonance imaging (MRI) systems. Quantum MRI will rely on the entanglement of the electromagnetic field to create images with higher resolutions than classical MRI machines. Current MRI scanners use strong magnetic fields, magnetic field gradients, and radio waves to generate images. Quantum ghost imaging is one possible path toward quantum MRIs. Quantum ghost imaging uses entangled photon pairs in which only one member of the pair interacts with the object. Precise timing is required to identify the entangled pairs. When the pairs have been detected, the image can be reconstructed.

Nitrogen-Vacancy (NV) Centres

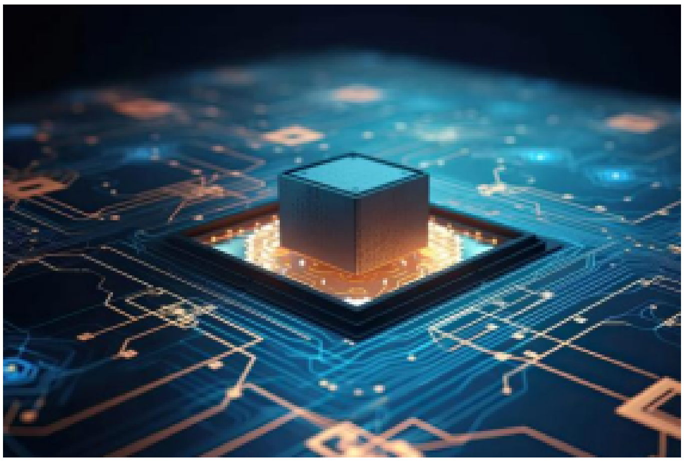
Modern innovations are making new quantum sensors and applications possible. One of the newer technologies uses Nitrogen-Vacancy (NV) centres, which can be fabricated within diamonds. To form an NV centre, a carbon atom in a pure diamond lattice is replaced with a nitrogen atom and another adjacent one is removed. This nitrogen paired with the vacant spot can now work as an incredibly sensitive magnetometer. It can use electron spin to detect tiny changes in magnetic fields.

NV centres can detect changes in magnetic field strength that are 50 million times smaller than Earth's, even in the presence of the Earth's magnetic field in the background. In the context of a camera lens, that kind of sensitivity is equivalent to having a single lens that would let you stand in one place and zoom out wide enough to capture all of Mount Everest in a single image, and also zoom in close enough to see a single human hair clearly at the top of the mountain.

NV centres can find applications in medical devices to help diagnose disease earlier. It can also be used to navigate by sensing the Earth's magnetic field while flying in an aeroplane, driving a car or a ship, and even underwater and underground. These quantum sensors can also be used to measure the tiniest magnetic fields within living cells, which may speed up drug discovery.

Other kinds of new-generation quantum sensors are in various phases of development. They are expected to detect minute changes in properties like acceleration, rotation, pressure, electric fields, temperature etc. There are many applications of these next-generation quantum sensors, with engineers regularly developing new ways to use them.

QUANTUM COMPUTING: COMPUTING THE INCOMPUTABLE (or at least, impossible to compute in a short time)



Quantum computing is an emergent field of cutting-edge computer science harnessing the unique principles of quantum mechanics to solve problems beyond the capabilities of even the most powerful classical computers. It contains a range of disciplines, including quantum hardware and quantum algorithms. While still in development, fully realised quantum computers should be able to process massively complicated problems at orders of magnitude faster than modern machines. Challenges that take classical computers thousands of years to complete might be reduced to mere minutes by using quantum computers. A primary difference between classical and quantum computers is that the latter use Quantum Bits (qubits) in superposition instead of standard binary bits (zeros and ones) to encode exponentially more data.

While quantum computing does use binary code, qubits process information differently from classical computers. But what are qubits and where do they come from?

Qubits

Like an ordinary bit, a qubit can store either a zero or a one, but it can also be a weighted combination of zero and one simultaneously. When combined, qubits in superposition can scale exponentially. Two qubits can store four bits of information, three can store eight, and four can store sixteen. That is to say, 'n' qubits can store the equivalent of 2^n bits of data. However, each qubit can only output a single bit of information at the end of the computation.
Generally, qubits are created by manipulating and measuring quantum particles such as photons, electrons, trapped ions and atoms. Qubits can also engineer systems that behave like a quantum particle, as in superconducting circuits. Some instances of different kinds of qubits used in quantum computing today include Superconducting Qubits (made from superconducting material), which operate at extremely low temperatures and are favoured for their speed in performing computations and finetuned control; and Trapped Ion Qubits which are particles that can be used as qubits and are noted for their long coherence times and high-fidelity measurements.

Key Principles of Quantum Computing

When discussing quantum computers, it is important to realise that quantum mechanics does not work like traditional physics. The behaviours of quantum particles often look bizarre, counterintuitive or even impossible to us. Thus, describing the behaviours of quantum particles presents a unique challenge. Therefore, to understand quantum computing, it is important to understand a few key terms first: Superposition, Entanglement, Decoherence and Interference.

Superposition

A qubit itself isn't very useful. But it can place the quantum information it holds into a state of superposition, which is a combination of multiple possible configurations. Groups of qubits in superposition can create complex, multidimensional computational spaces, where complex problems can be expressed in new ways. This superposition of qubits gives quantum computers their inherent parallelism, allowing them to process many inputs simultaneously.

Entanglement

Entanglement is the ability of qubits to correlate their state with other qubits more strongly than regular probability allows. Entangled systems are so intrinsically linked that when quantum processors measure a single entangled qubit, they can immediately determine information about other qubits in the entangled system.

Decoherence

Decoherence is the process in which a system in a quantum state collapses into a non-quantum state, allowing quantum computers to provide measurements and interact with classical computers. It happens when a quantum system is measured or affected by other environmental factors (sometimes unintentionally).
Interference
An environment of entangled qubits placed into a state of collective superposition structures information in a way that looks like waves, with amplitudes associated with each outcome. These amplitudes become the probabilities of the outcomes of a measurement of the system. These waves can build on each other when many of them peak at a particular outcome (Constructive Interference), or cancel each other out when the peaks and troughs interact (Destructive Interference).

So, How These Principles Work Together?

To understand quantum computing, assume that two counterintuitive ideas can both be true. The first is that objects that can be measured—qubits in superposition with defined probability amplitudes—behave randomly. The second is that objects too distant to influence each other—entangled qubits—can still behave in ways that, though individually random, are somehow strongly correlated.
A computation on a quantum computer works by creating a superposition of computational states. A quantum circuit is designed so that all the wrong answers are suppressed by destructive interference, leaving only the correct answers. This circuit uses operations to generate entanglement, which causes interference between the 7 various states according to the rules of the algorithm being used. Many possible outcomes are cancelled out through

interference, while others are amplified. The amplified outcomes are the solutions to the computation.

Classical vs. Quantum Computing

When dealing with a complex problem like factoring large numbers, classical bits get overloaded as they have to store a lot of information. However, qubits behave differently. Because of the ability of superposition, a quantum computer that uses qubits can approach the problem in ways different from classical computers. For example, while a classical computer with three bits can represent only one of eight possible states at a time, a quantum computer can represent all eight possible states simultaneously in a superposition state. This concept (Quantum Parallelism) along with Quantum Interference (interaction between the states within a superposition), allows quantum computers to perform certain computations much faster and with less hardware than classical computers. This fundamental difference in data processing is what sets quantum computers apart, and it has significant implications for the kinds of tasks and calculations they can perform more efficiently.

Additionally, quantum computers benefit from another important concept: Quantum Entanglement, which allows a group of qubits to be interlinked, so that their properties become correlated. Suppose there are two such entangled qubits. When a quantum computer measures or changes a property of one qubit (e.g., spin, position, or polarization), it will then instantaneously change that property of the other one as their properties and states are correlated or entangled. Quantum computers can utilise this instantaneous correlation to improve their processing power. It allows quantum computers to solve complex problems more efficiently by performing multiple calculations simultaneously. Additionally, entanglement enhances the precision of quantum algorithms, contributing to faster and more accurate problem-solving in fields like cryptography, optimisation, and material science.

To put things into perspective, imagine you have a treasure chest with 1000 keys. A classical computer is like someone who tries each key one by one. If there are 1000 keys, he/she has to check each one individually, and it could take a lot of time to find the right key.

A quantum computer, on the other hand, is like someone with magical abilities, who can somehow try all 1000 keys at once. Instead of checking each key individually, it explores multiple possibilities simultaneously. Thus it can find the correct key much faster.

Quantum computers are scaling rapidly. Soon, they will be powerful enough to solve previously unsolvable problems. Which presents a global challenge: quantum computers will be able to break some of the most widely-used security protocols in the world. What is a possible way forward?

QUANTUM CRYPTOGRAPHY: SECURING THE UNSECURED

Again, Quantum Mechanics comes to our rescue. To date, traditional data encryption has generally been effective in maintaining secure communications in most cybersecurity settings. However, the rise of quantum computing has made even the most secure traditional cryptographic algorithms vulnerable. As discussed in the previous section, quantum computers can potentially solve complex problems orders of magnitude faster than our current fastest classical computers. While such computers were once only theoretical, experts now believe that it might be only 20 to 50 years away before we fully enter the quantum age.

The threat posed to traditional security systems by quantum computing was first described by Mathematician Peter Shor in 1994. Today's cryptosystems can be divided into two main categories: Symmetric Systems, which use one secret key to both encrypt and decrypt data; and Asymmetric Systems, which use a public key that anyone can read and private keys that only authorised parties can access. Both types of cryptosystems create these keys by multiplying large prime numbers. Factoring large numbers requires huge computing power, which acts as a strong deterrent against eavesdroppers or hackers who

might get access to the encryption keys.
Even the most powerful supercomputers on earth would take thousands of years to mathematically break modern encryption algorithms like the Advanced Encryption Standard (AES) or Rivest-Shamir-Adleman (RSA). According to Shor's Algorithm, factoring a large number on a classical computer would require so much computing power it would take a hacker many lifetimes to even come close. However, a fully functional quantum computer can potentially find the solution in only a matter of minutes. For this reason, quantum cryptography is likely to find uses wherever there is use for any form of cryptography at all. From corporate information to state secrets, if anything must be kept secure when quantum computing renders existing cryptographic algorithms obsolete, quantum cryptography may be our only alternative to secure private data.

TYPES OF QUANTUM CRYPTOGRAPHY

Quantum Key Distribution (QKD)

Quantum Key Distribution (QKD) is the most common type of quantum cryptography. It is not typically used to encrypt data itself but is rather a secure way for enabling two parties to collaboratively produce and share a key to encrypt and decrypt messages.
QKD works by transmitting many light particles, or photons across a fiber optic cable between two parties. Imagine two people, Rob and Bob, who need to establish a secure connection. Rob sends polarised photons over a fiber optic cable to Bob. This stream of photons travels in a single direction and each one represents a single bit, or qubit, of data —either zero or one. Polarised filters on Rob's side change the physical orientation of each single photon to a specific position. When a photon reaches Bob, it travels through a beam splitter, which forces the photon to take one path or another randomly into a photon collector. Bob then sends Rob the data regarding the sequence of the photons sent, who then compares that with the emitter, which would have sent each photon.
Photons in the wrong beam collector are discarded; what's left is a specific sequence of bits. This bit sequence can then be used as a key to encrypt data. Any errors and data leakage are removed during a phase of error correction and other post-processing steps.
Now, should someone, let's call him Fob, be eavesdropping, Rob and Bob will know that someone is watching because it is impossible to observe a quantum state without also affecting it. In this way, QKD systems are considered to be un-hackable. Although the benefits of QKD have been proven in both laboratory and field settings, many practical challenges are preventing widespread adoption, most notably infrastructure requirements. Photons sent across fiber optic cables degrade over distances of about 248 to 310 miles. However, recent advancements have extended the range of some QKD systems across continents by using secure nodes and photon repeaters.

Quantum Coin-flipping

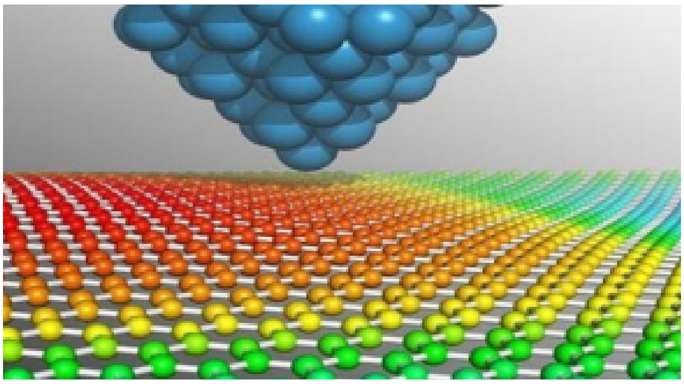
Quantum coin-flipping is a type of cryptographic primitive (something of a building block for algorithms) that allows two parties who do not trust each other to have a fair coin flip. These parties are not physically near each other and use quantum communication channels to interact. Imagine if Rob and Bob are talking on the telephone and want to bet on a coin toss, but only Rob can access the coin. If Bob bets heads, how can he be sure that Rob won't lie and say that the coin landed on tails, even if it lands on heads?
This type of 50:50 bet can accomplished by Rob sending Bob a series of photons polarised based on one of two orientations, rectilinear and diagonal. The rectilinear measurement orientation has vertical (1) and horizontal (0) polarizations. Similarly, in the diagonal measurement orientation, there are two diagonal polarizations, one encoding '1' and the other '0'. At first, Rob generates a random sequence of 1's and 0's, chooses an orientation and then assigns each photon a polarization based on the bit value (e.g. if the orientation chosen is rectilinear, then he makes a photon vertically polarised if he sees 1 or otherwise, 0). On the other side, Bob also chooses an orientation plus a polarization filter from that orientation to read each photon. The trick is, for each bit, half the time he will choose the right orientation and the other half the wrong one. If he makes a table containing two columns, each representing an orientation, some of the measured photons will fall in one column and the rest in the other one. From this, he has to guess which orientation Rob originally chose. If either Rob or Bob suspects the other of cheating, they can compare the readings taken by the polarising filters for

authentication. Here is an interesting video which explains this in detail: What is a quantum coin toss?

Additional types of quantum cryptography

Researchers continue to explore other types of quantum cryptography incorporating direct encryption, digital signatures, quantum entanglement and other forms of quantum communications. Other types of quantum encryption include Positionbased Quantum Cryptography, Device-independent Quantum Cryptography, Kek Protocol, Y-00 Protocol etc.

SCANNING TUNNELLING MICROSCOPY (STM): MAKING THE INVISIBLE VISIBLE



Scanning Tunnelling Microscopy (STM) allows researchers to map a conductive sample's surface atom by atom with ultra-high resolution, without the use of electron beams or light. Since its invention in 1981 by two IBM scientists named Gerd Binnig and Heinrich Rohrer, it has revealed insights into matter at the atomic level for almost forty years. By scanning a very sharp metal wire tip very close to a surface, and by applying an electrical voltage to the tip or sample, STM can image the surface at an extremely tiny scale – down to resolving individual atoms.

Binnig and Rohrer aimed to create a tool for studying the local conductivity of surfaces. The surface of gold was chosen for their first image. When the image was displayed on a television monitor, they observed rows of precisely spaced atoms and observed broad terraces separated by steps one atom in height. In this way, they discovered in the STM a simple method for directly imaging the atomic structure of surfaces. Their discovery ushered in a new era for surface science, and they were awarded the Nobel Prize for Physics in 1986.

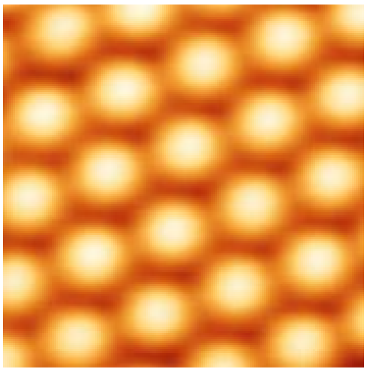


Image by STM: Atoms on the surface of a crystal of Silicon Carbide (SiC) are arranged in a hexagonal lattice and are 0.3 nm apart.

STM is a remarkable example of a real-world application of a process known as Quantum Tunnelling. It is a quantum mechanical phenomenon in which an object such as an electron or atom passes through some barrier (in this case, a tiny gap between the tip and the surface) that initially doesn't seem to be passable due to the object not having sufficient energy to pass or surmount the barrier. Its macroscopic analogue could be someone walking through a solid wall of brick. Electrons, by contrast, have a wave-like character that makes them a "fuzzy" cloud of probability (unlike a person), so they can actually exist on both sides of the barrier simultaneously and therefore have a non-zero probability of moving across the barrier even if the barrier energy is higher than the total energy of the electron.

So, how does STM work? At first, a sharp conductive probe is brought very near to the surface of a conductive specimen. A potential difference is created, forcing electrons to traverse the gap between them. When the tip is sufficiently near the surface (usually <1 nm away), the fuzzy electron clouds of the first atom of the tip and surface begin to overlap. Applying a bias voltage between the tip and the surface in this configuration produces a current because electrons are driven to tunnel through the potential barrier from the tip to the surface via the overlapping electron cloud. This tunnelling current is highly sensitive to the gap between the probe tip and surface, varying exponentially with the tip-sample distance. As the tip scans line by line across the sample surface, the intensity of the tunnelling current maps the sample's electronic density of states.

STM operates in two distinct modes: Constant Height Mode and Constant Current Mode. The former is generally used when the sample surface is very smooth. In this mode, the probe tip stays at a fixed height while quickly running scans across the sample. By measuring changes in the intensity of the tunnelling current as a function of the position coordinates (x,y) and bias voltage, researchers can construct an image of the electronic density of states of the sample surface, defects, frontier molecular orbitals, and more.

The more popular mode is known as the Constant Current Mode. In this mode, the tunnelling current is held constant using a feedback loop system that adjusts the distance between the tip and the surface. If the tunnelling current exceeds the target value, the feedback control system will increase the distance between the tip and the sample; if the tunnelling current is less than the target current value, the feedback control system will bring the tip closer to the surface of the sample. The resulting threedimensional distance profile as a function of the (x,y) position can help researchers measure a wide range of characteristics, including surface roughness, defects, and the size and conformation of molecules on the surface.

STMs may also be categorised by the different environmental conditions they operate under. Ambient STMs typically function in air or other gases at near room temperature.

Ultra-high vacuum (UHV) STMs, on the other hand, operate under very high vacuum. This is often done in highly specialised UHV systems where the sample is grown or etched and then imaged in situ. Their operation in vacuum allows them to operate across a very wide temperature range, from near absolute zero to over 1000°C.

Uses of STM in Research

STM was initially used to study the topology and atomic structure of surfaces of different metals. It allowed researchers to discern the atomic-scale properties of materials, including surface roughness, defects, and surface reaction pathways. But over the years, STM began to be employed for a variety of applications outside of atomic-scale imaging. It has been used to assemble and manipulate individual atoms on a surface, leading to advances in nanotechnology, such as the generation of nanostructures like quantum corrals and molecular switches. Additionally, STM can be used to construct contacts on nanodevices by depositing metals (e.g., gold, silver, tungsten etc) in specific patterns. Researchers have also used STM to trigger chemical reactions and study the resulting reaction mechanisms at the molecular level. Since its discovery, the STM has been responsible for big breakthroughs in nanotechnology and has enabled novel research across various disciplines, including semiconductor science, electrochemistry, surface chemistry, and more.

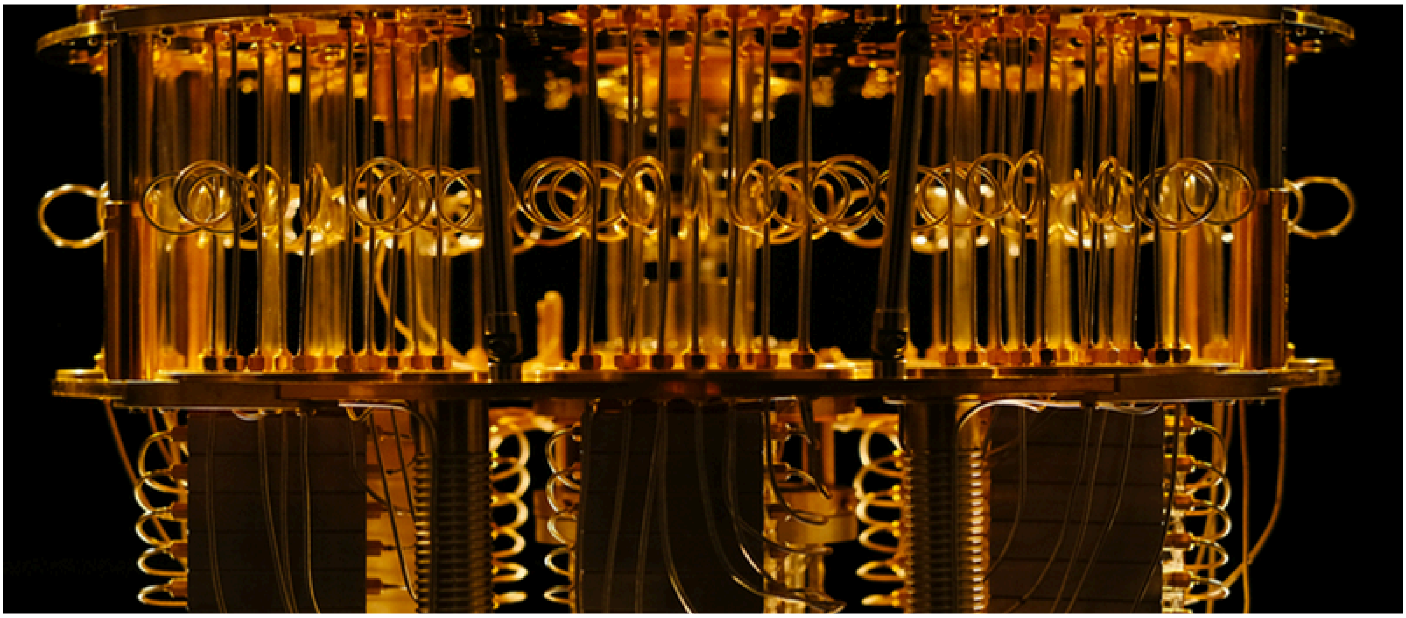
CONCLUSION

In this article, we briefly touched on some important quantum technologies. The widespread adoption of these technologies everywhere certainly comes with many benefits. However, there might be some obstacles too. For example, quantum computers must be kept at near absolute zero temperatures to maintain qubits in their delicate quantum states and prevent them from providing inaccurate results or errors due to unintended decoherence. The economic cost of installing and maintaining a single quantum computer hinders their implementation. Another problem is the dearth of cross-compatible software that works well between different quantum computers, due to the field being still new. Quantum algorithms might need some fine-tuning to work effectively on different or similar types of quantum computers from other vendors. There is also a lack of a skilled quantum workforce to handle these technologies.

Lastly, let's ask how these technologies might impact human society at large. For one, they are expected to drive innovation across various industries, leading to new products, services, and possibly entirely new industries, transforming the global economy and job market. However, they could also be used to increase existing global inequalities. For example, the rise of quantum computing could compromise data secured by traditional cryptographic methods on a global scale. Countries and corporations with access to these advanced tools may gain unfair advantages over others. While we reach new heights of quantum supremacy, it is also essential to keep in mind the societal consequences they bring with them. As responsible global citizens, we must ensure that these powerful tools are developed and utilised in ways that benefit humanity as a whole.

Are we ready for *Quantum Computation?*

By Aditya Aryan, 137Inverse



Understanding Quantum Computing

Firstly, it is essential to understand how QC differs from classical computers, which are the devices we use daily; they operate on bits that represent information as either a 0 or 1. These bits follow the principles of Boolean algebra, the mathematical framework that forms the basis of classical computation. Tasks like encryption, data processing, and algorithmic problem-solving rely on manipulating these bits in a step-by-step fashion.

Quantum computers, however, operate completely differently. Instead of bits, they use quantum bits, or qubits, which represent a 0, a 1, or both simultaneously, using a quantum phenomenon known as superposition. Qubits can also be entangled, meaning the state of one qubit is directly related to the state of another, irrespective of the distance between them. These two properties enable quantum computers to process vast amounts of data simultaneously, performing calculations that would take classical computers millions of years in seconds or minutes.

The Security Implications: A Quantum Threat

All this poses a direct and severe threat to traditional cybersecurity. Public key cryptography, the cornerstone of modern digital security, relies on the mathematical difficulty of certain problems. For instance, RSA encryption depends on the challenge of factoring large prime numbers, a task that classical computers struggle with due to its exponential time complexity.

However, quantum computers can solve these problems far more efficiently using algorithms like Shor's algorithm, which can factor large numbers faster than the best-known classical algorithms, effectively rendering RSA and other public key cryptosystems obsolete.

This not only undermines the security of widely deployed encryption algorithms but also threatens to make current security systems redundant. If quantum computers can easily break these encryptions, the confidentiality and integrity of sensitive data—from personal information to government secrets—would be compromised, leading to potentially catastrophic consequences.

The Quantum Computing Arms Race

Quantum computers could radically shift the balance of power in cybersecurity. The country or entity that first achieves quantum supremacy would gain a strategic advantage akin to the possession of the atomic bomb. The stakes are incredibly high: The entity that controls quantum computing will have the ability to decrypt previously secure communications, potentially gaining access to vast amounts of confidential information and disrupting critical infrastructure.

Q-Day, short for "Quantum Day" (aka Y2Q), refers to the hypothetical future date when quantum computers will become powerful enough to break current cryptographic algorithms that secure most of the world's digital information.

We already see signs of a quantum computing arms race. Governments and corporations worldwide are investing heavily in quantum research, vying to be the first to harness it.

This race has prompted concerns about the security of encrypted data in the present day. Even if quantum computers are not yet capable of breaking all current encryption methods, the knowledge that they will likely be able to in the future has led to the practice of "harvest now, decrypt later" (HNDL). Adversaries may be collecting encrypted data today with the intent of decrypting it once quantum computers become sufficiently powerful, putting long-term data security at significant risk.

Defying the Classical computational Paradigm

It is important to understand that quantum computers are not just faster or better versions of classical computers; they represent a fundamental shift in how we understand and perform computation by allowing parallel processing on an unimaginable scale.

This is the dawn of a new era of computation, and the shift is not just a matter of increased speed or efficiency; it's a complete rethinking of computational possibilities. Quantum algorithms can tackle problems that are intractable for classical computers, opening up new avenues in fields such as materials science, cryptography, and artificial intelligence. However, this potential also comes with profound risks, especially in the realm of cybersecurity.

Preparing for the Quantum Shift: The Role of Cryptographers

Recognising the existential threat posed by quantum computing, an army of mathematicians, cryptographers, and computer scientists is working behind the scenes to develop quantum-resistant cryptography. These new cryptographic methods aim to secure communications and data even in the face of quantum attacks.

One approach is post-quantum cryptography, which involves developing new algorithms that are believed to be secure against both classical and quantum computers. These algorithms rely on mathematical problems that, as far as we know, quantum computers cannot solve efficiently, with the goal of replacing vulnerable cryptographic systems before quantum computers become a practical threat.

Another approach is quantum cryptography itself, particularly Quantum Key Distribution (QKD), which creates secure communication channels that are theoretically immune to eavesdropping. In QKD, any attempt to intercept the communication alters the quantum state of the particles being transmitted, alerting the parties involved and ensuring the security of the key exchange.

However, implementing new cryptographic standards across the vast, interconnected infrastructure of the Internet is a daunting task, requiring coordination between governments, industries, and international organisations. Moreover, there is the question of whether these new methods will truly be secure against future quantum advancements.

The Urgency of Preparedness: Are We Ready?

As we approach the era of quantum computing, we have understood that the threats are not hypothetical, with developments in quantum computing accelerating rapidly.

The world needs to ask: Are we ready for this quantum shift? The answer will determine not only the future of cybersecurity but also the broader landscape of global power and technological progress. The time to prepare is now, before quantum computers move from theoretical to practical and before the quantum threat becomes a quantum catastrophe.

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Quanta, India, and Life

An interview with Professor Baladitya Suri of the Instrumentation and Applied Physics Department, IISc.

By Jahin Sadat Mollah,
Gunda Sai Vinay,
Ensemble

The National Quantum Mission is all the hype these days. Could you tell us how IISc contributes to the Mission?

NQM itself has four verticals under it. One is Quantum Computation which also includes aspects of quantum simulations and then there is Quantum Communications and Quantum sensing. This includes measurement sensing of at the quantum level. And then Materials for Quantum Technologies which is a vertical wherein all research into new materials lies, which gets integrated with the other three verticals for applications. Let's say, someone has been working with graphene, say single and two layers of graphene. The question becomes, how do we build new Quantum Technologies, sensors, qubits or whatever using this as a platform. That’s where the integration with other verticals comes in. IISc has people working in all these verticals: On the computation side, we have people working on the superconducting qubits, which is the most mature platform for quantum computation worldwide. All the ‘big-tech-people’ in this area, IBM, Google and, to an extent, even Intel and Microsoft, all of them have intersections with superconducting qubits. Professor Vibhor Singh in Physics and I work in this area. In collaboration with Professor Vijay Raghavan from TIFR and other investigators, we are part of a proposal submitted to the National Quantum Mission. Then, we have Professor Shankar Selvaraja from CENSE and Professor Chandra Shekar, an adjunct IAP faculty. They are interested in Photonic Quantum Computation, with optical elements, states of light, acting as qubits. That's a different paradigm altogether, though. Photonics and superconducting qubits are the two most dominant platforms worldwide followed by trapped ions. So IISc’s two for three, right now. On the communication side, Professor Varun Raghunathan in ECE has been working on experimental aspects of Quantum Communications. Certainly there are other people too, working in information theory, error correction information, and so on. Quantum sensing is where Akshay Singh comes in. Now, Quantum sensing and Communications work very well in conjunction because you will need sensors operating at the quantum limit for some of these measurements like, detecting single photons etc. Sources and detectors for single photons or detecting extremely small magnetic fields is pretty much what Quantum Sensing is mostly about. There’s Professor Ambarish Ghosh, Akshay Nayak; essentially, we have a whole bunch of people working on that front. For materials, of course, we have a lot more people across various departments: Physics, IAP, Materials engineering, Solid State & Structural Chemistry, CENSE. All these departments have people working on the material side of things.

So, it's a fairly comprehensive participation. We should say from the mission point of view, IISC’s contribution will be quite significant.

Quantum computation in its current state, at least in India, is a relatively new field. It's not entirely fleshed out. How does that work out for newer people trying to enter the field?

Well. This applies to all fields, doesn’t it? The literature out there, when it comes to research, is always inaccessible to somebody who is getting started. You might naively think that a Quantum Field Theory course is going to get you ready for doing Supersymmetry. That's not entirely the case. Because, simply, there is a basic set of things that a Field Theory course will teach you. But after that, you will have to apply those basic principles and expand your knowledge to catch up with the existing research. The same is the case with Quantum Computation. Let’s say here in IISc, we have the Quantum Technologies courses. Now, after you finish your undergraduate program or after the Masters in Quantum Tech Program or perhaps even during this exercise, you grasp the fundamentals through these basic core courses. Then you take

“You might naively think that a Quantum Field Theory course is going to get you ready for doing Supersymmetry. That's not entirely the case.”

some electives to expand your knowledge. After that, you can straight away start contributing by participating in research. That is the only way. You have to learn on the fly, on the job. That is the idea. Courses will only get you started. Now, there are many, many institutes where such an access to courses is not available. There are several certification programs that are around these days. But those are not to be mistaken for full-fledged courses happening in institutes like IISc or IIT Madras or IISER Pune. Those are full-fledged courses. Either way, once you go through the basics of Quantum Technologies and understand the fundamental principles, you straight away can start negotiating with the frontier research and learn more advanced techniques on the job and start contributing. There won't be any courses at that level. This is true for all fields and the same holds here.

This brings me to my next question: How does teaching and your enthusiasm for teaching fit into this big picture, wherein you must balance research, teaching and other things well?

To me, teaching is not very different from research. In the sense that, at least when I was growing up, when I was in your place, I was exposed in IIT Madras to some very, very good teachers, who are quite legendary. You might have heard of Professor V Balakrishnan. Yes, who has his NPTEL lectures on many subjects like classical mechanics, quantum mechanics. I sat in his classes; I learned from him. And what I noticed is that when research on a topic deepens their understanding and that gets carried into the classroom where they can convey something, without getting lost in the nitty-gritty details. They can first give you a bigger, more comprehensive picture and then take you through the details. Teaching fits into a larger framework of higher education which is all about preparing you for research. That's the way I look at it. Let's say you are undergrad, in a BS research program. The program itself is called BS research, and the courses are meant to prepare you for research. With that perspective, any course must bridge a gap. It should give you the fundamentals, but should also give you a sneak preview of where all this fits in. In that sense, what you are doing is you are whittling down the larger, bigger problems into a framework, which the students can understand. And this, to me, involves a lot of research. Arranging material in a fashion where you go from topic-to-topic and at the end, something big comes out of it involves research! In my opinion, teaching and research should not be thought of as orthogonal activities, and one helps the other. In fact, it's great, even for deepening your understanding of the subject. Let's say you're working on a problem. Many a time, even if you understand the basics very well, you get a fresher perspective and a deeper understanding of how to tackle this problem. Teaching contributes there. Any good teacher is not just parroting what they know from memory, but they're in the moment: engaged with the class in a discussion, and through that process, through the questions and answers that the students pose, and through thinking on your feet, you are actually exploring. I teach thermodynamics and basic physics to UGs every year. I can safely say, that of the 120 people in the class, I get the most out of that experience!

"Teaching and research should not be thought of as orthogonal activities..."

Well, how would you advise sophomores and freshers you see in class to start contributing to research? They're certainly very inexperienced and lacking in knowledge about these new fields: quantum materials, quantum information and so on.

This is a very old problem. Every scientist wishes that they were born 100 years before, because with this current intellect, if I were born 100 years back, I could have made a huge impact on physics and that is true. Because if you look at the entire gamut of physicists, who worked on, say the birth of quantum mechanics, you may recall names of some legends, like Einstein, Planck, Bohr, Heisenberg, Schrodinger and Dirac. These are people who you remember, but there are a whole bunch of others like Cramer etc who also contributed. Now what happens as the field progresses is frontiers are pushed forward, but core education, at the undergraduate level and master's level, remains in the fundamentals. These seem disconnected from the frontiers and that is where I meant that people who are doing active research, should contribute to teaching, because that is where the gap gets bridged. If you don't do that, if you take teaching as a full-time activity, with no research, or research as a full-time activity, with no teaching, this gap can never be bridged.

The purpose of, admitting batch after batch is not to clone all of them in the same model, right? We won't say a batch, which took BS research in 2010 and the batch taking the course in 2024 be taught the same courses at the same level in the same way. Why? I'm not talking about the socioeconomic situation of the students. That's not what I'm talking about. Fields have moved forward. So, the curricula have to be updated. You cannot drag all the students to the frontier, but at least bring them slightly closer. So that from here, they can go.

This is where we need researchers to teach and bridge the gap I mentioned. Also, you should not skip steps, in the sense you should not worry as an undergrad about contributing right away. Just focus on the fundamentals and join a research group. Start dealing with real world present day, frontier problems and that's enough.

Learning is a very non-linear process, but when we start analysing things, we tend to do it very linearly. This is the problem in the sense that we are learning non-linearly. But when we think I must learn something, we try to lay down a linear path from here to that and that is where the problem is.

> "You cannot drag all the students to the frontier, but at least bring them slightly closer."

Finally, I'll ask something about you. You weren't always in is like into Quantum Computation, right? You switched from particle physics?

Yeah, for the first three years of my PhD I was trying to be a particle physicist. I was training to be that but then due to various reasons, mainly due to the economic recession in Europe and U.S., universities cut down their intake of graduate students largely, because of the funding cuts, and because the teaching load on all the existing students was very high. That prompted me to look for areas where there was funding which led me to Quantum Computation.

What I get from that, is that the field that we end up in, is strongly morphed by the situations that we are in, and the people we meet along the way who may influence us, right? How important is it to keep an open mind in research?

One should not be attached to one field, since that's the word you are using. It goes both ways, right? For example, when fields change, one should always be open to learning new things. That's a universal principle. But, getting attached to a problem is a good thing in some situations. Once you are making progress in some direction, if you are not attached to that, you will not make the effort necessary to go forward. In that sense, you should be passionate about the problem that you are working on. But as a scientist, you should also be open to the possibility that that may not work. To me, that's not a problem, because research has both possibilities.

Bala addressing an audience at IISc.

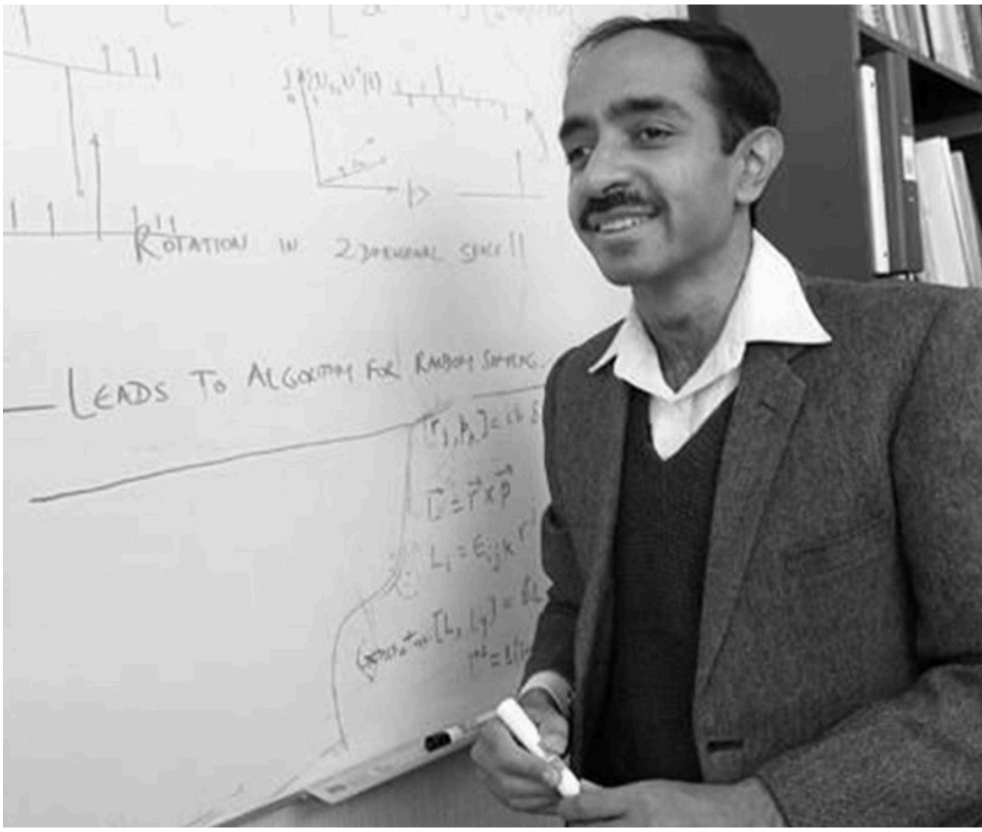
You should be equanimous to both possibilities: you make your sincere effort while being open. Because if you completely close your mind and say ‘this has to work’, nature has no rule to oblige and say that it will work. So, you have to take the inputs that you are getting from the data and take a call at some point to say, ‘maybe this doesn't work’. But to know whether something works or not, you will need to put in the initial time for research. In fact, if you take the entire solid angle from one field of research, most of it is being used for exploration and then people latch on to some smaller solid angle and then see that there may be some life here. That's how it goes. So if you actually take a survey of all the projects that are floated and all the projects that, ultimately succeed, the fraction is quite small. That's natural. So, I would say you have to be open to learning new things. But at any stage, like all human pursuits, you are guided by what you like. If you like something, you should pursue it. But you should also be open to abandoning your pursuit if the data shows you that this may not work. That’s all basically being receptive. Science is not about being very obstinate, that works in certain fields, probably, but in exploratory science, you cannot be that way. You have to be very open-minded to be able to jump on a new idea and try to pursue it and to abandon old ideas. In fact, the progress in science, has been hindered not by the lack of discoveries, but by people getting attached to older ideas. Most of our energies have actually been spent in, you know, changing their magnetization from 180 degrees out of phase, to being in phase. So that's where all the work is done. But things usually turn out well and we stay hopeful.

GROVER'S ALGORITHM

A look at an important quantum algorithm and its unexpected appearance in natural systems

By Chinmay Panchariya, Patricia Kshetrimayum, Ritabrata Saha, Ensemble

Lov Grover, the progenitor of numerous essential algorithms ubiquitous in quantum computing in the present age.



INTRODUCTION

Grover's Algorithm, discovered by Lov Grover, is a quantum search algorithm for finding a target item that satisfies certain properties out of an unstructured database. The advantage of this algorithm is that the number of iterations needed to reach the target state is $O(\sqrt{N})$ for a database of size N. Any Boolean algorithm would require O(N) binary queries to accomplish the same task starting from an unbiased state, so this is a square-root improvement in the computational efficiency. Furthermore, the algorithmic evolution is at a constant rate along the geodesic from the initial state to the final state, taking place in the two-dimensional subspace (of the total N-dimensional space) formed by the uniform state and the target state. That makes it the optimal solution to the problem.

Suppose we have an n-qubit system. A function f is defined on the n-dimensional qubit strings represented by $f : \{0,1\}^n \to \{0,1\}$ such that for some $x \in \{0,1\}^n, f(x) = 1$ and for the rest $f(x) = 0$. Now, our aim is to find the qubit state satisfying $f(x) = 1$. Let $|t\rangle$ be the only target state that gives $f(|t\rangle) = 1$ and $\forall |x_i\rangle \neq |t\rangle, f(|x_i\rangle) = 0$ .The total number of input strings for this algorithm is $N = 2^n$.

We outline Grover's algorithm below:

Step I: The initial step is to create a quantum state which is the uniform superposition of all the computational basis. These bases are the possible 2^n inputs. This can be done by applying Hadamard gate (H) to one of the inputs.

When n = 1, the matrix form of the gate is:

$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

For an n-dimensional qubit string, the Hadamard matrix is the tensor product represented as $H^{\otimes n}$. Applying this matrix to one of the inputs will result in a linear combination of all the inputs where each of the coefficients are the same. This implies that all inputs will have same amplitude. Let $|s\rangle$ denote the uniform superposition of inputs $|x_i\rangle$, then we have:

$$|s\rangle = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} |x_i\rangle \implies |s\rangle = \frac{1}{\sqrt{N}}|t\rangle + \frac{1}{\sqrt{N}} \sum_{i=0}^{N-2} |x_i\rangle$$

Here $|x_i\rangle \neq |t\rangle$

Step II: The next step is the Oracle operation. Oracle is like a black box. It identifies the target state and flips its sign as follows:

$$|s\rangle = -\frac{1}{\sqrt{N}}|t\rangle + \frac{1}{\sqrt{N}} \sum_{i=0}^{N-2} |x_i\rangle$$

Step III: The final step is to apply the diffusion operator: $(2|s\rangle\langle s|) - 1)$.

This operation increases amplitude of the target state.

All these steps are iterated until the probability of the target state is very close to or equals 1.

Number of Iterations:

It can be observed that Step II and III together can be written in the form of reflection operators R_s and R_t for Q queries. Thus, Grover's algorithm gives us:

$$|t\rangle = (-R_s R_t)^Q |s\rangle$$

$R_t = I - 2P_t$ (called the oracle reflection operator) and $R_s = I - 2P_s$ (called the diffusion reflection operator). The projection $P_t = |t\rangle\langle t|$ operator represents the potential energy and $P_s = |s\rangle\langle s|$ represents the isotropic kinetic energy. If $|t\rangle$ and $|s\rangle$ are represented in 2-dimensional Hilbert space, then the overlap between the states is measured by $cos(\theta)$, given by $\langle s|t\rangle$ which should be maximized after Q iterations.

Earlier equations give us $cos(\theta_0) = \langle s|t\rangle = \frac{1}{\sqrt{N}}$,where θ_0 is the initial angle between $|t\rangle$ and $|s\rangle$. We aim to maximize overlap between the equilibrium and target states. Number of iterations(Q) required to do so are solution of:

$$(2Q+1)\sin^{-1}\left(\frac{1}{\sqrt{N}}\right) = \frac{\pi}{2}$$

We get the following numeric solutions (note the values):

Q = 1 → N = 4, Q = 2 → N = 10.5, Q = 3 → N = 20.2

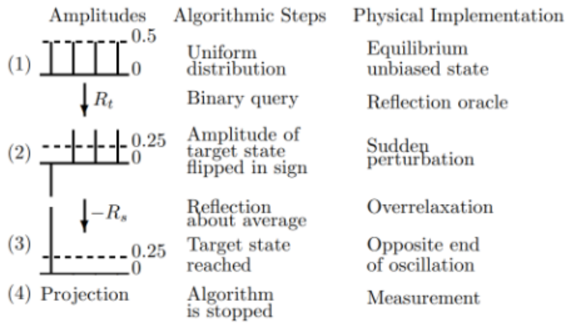


Figure 1: Diagrammatic representation of Grover's Algorithm

Understanding Process: Intuition for the algorithm's steps

First we introduce some changed notation: If we have an N -dimensional Hilbert space with |b⟩ being the target state (so, |b⟩ = |t⟩ from the introduction) and |s⟩ (as defined in the introduction) being the symmetric superposition of states such that:

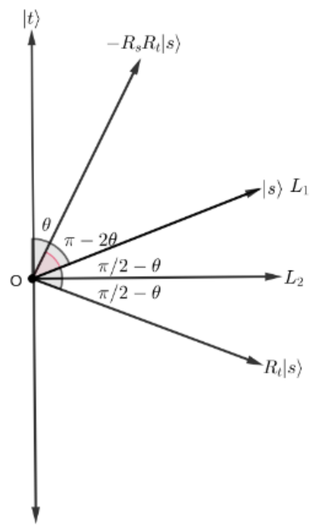
$$|b\rangle = [0...1..0]^T \text{ and } |s\rangle = \frac{1}{\sqrt{N}}[11..1...11]^T$$

And also:

$$U_b = 1 - 2|b\rangle\langle b| \text{ and } U_s = 1 - 2|s\rangle\langle s|$$

$U_b = R_t$ and $U_s = R_s$ are reflection operators (as defined in the introduction).

Consider the following figure:



Here, U_b flips the sign of the amplitude in the desired state, analogous to reflection along L_2 line, and corresponds to finding a suitable base for pairing amongst all. U_s operator base independent. It reflects amplitude about the superposition state |s⟩, analogous to reflection about L_1 line. We can relate it to rotation by an angle θ (determined by |⟨b|s⟩|).

Such rotation is performed Q times giving:

$$(-U_sU_b)^Q|s\rangle = |b\rangle$$

Grover in protein synthesis?

One of the most prominent natural systems where we see nature use Grover's search algorithm is for protein synthesis within a cell. DNA contains sequentially arranged nucleotide bases that carry genetic information. The process of protein formation can be generally classified into two stages: (a) The splitting of DNA - a complementary strand of mRNA is synthesized, replacing thymine with uracil. This mRNA then enters the cytoplasm, and along with tRNA and rRNA, facilitates protein synthesis. (b) A chain of amino acids is built as tRNA reads the mRNA sequence, matching its set of three bases (anticodon) with the complementary three-base sequence (codon) on the mRNA. Each time a match is found, the tRNA adds the correct amino acid to the growing protein chain, following the instructions provided by the mRNA.

What does Grover's Algorithm have to do with this process?

DNA, RNA, and proteins store information in the algorithm using specific sequences (or alphabets), similar to how a computer uses binary code (1s and 0s). DNA and RNA use four nucleotide bases whereas proteins are made from a set of 20 naturally occurring amino acids. When the processes mentioned in (a) and (b) take place, the system examines the different alphabets for a given number of queries. For example, in DNA to mRNA, the system will study the 4 available bases and try to find the key for a given nucleotide, thus giving query, Q = 1 and N = 4. Similarly, protein synthesis has Q =3, and we know that in this case, N is approximately equal to 20, which is also equal to the total number of amino acids participating in the process! Coincidentally, nature has adopted the fastest known algorithm for this unsorted search in the system!

How does this evolution take place exactly?

We know that the quantum evolution operator is exp(-iHt). However, the conservation of energy requires an overall phase of exp(-iHt) to cancel out, leaving only a relative phase between pairing and non-pairing bases to worry about (pairing bases would be the combinations AT, GC while all others would be non-pairing). The operator associated with the interaction of bases to gain stability by pairing turns out to be H_{int} (the interaction Hamiltonian), shown as:

$$H_{int} \propto (a^\dagger b + b^\dagger a)$$

Here $a, a^\dagger$ are the annihilation and creation operators between reactants' ground and excited states. Similarly, $b, b^\dagger$ are associated with a unit of quantum energy released or absorbed. The phase change ϕ while forming a bond can be associated with:

$$\exp(-iH_{int}t_b)\,|e\rangle\,|0\rangle = \phi|g\rangle|1\rangle$$

In this equation, |e⟩ and |g⟩ are the excited and ground state. Also, t_b is the time the two bases spend near each other such that the interaction Hamiltonian isn't negligible. Diagonalizing and solving gives us we get $\phi = \sqrt{-1} = i$ and eigenvalues $\pm\Delta E_H$.

Interestingly, ϕ is independent of ΔE_H and t_b , showing that the energy quanta released do not contain any phase information.

Here's a key assumption we make: Within these base pairs, multiple hydrogen bonds of different lengths are present. We assume that the pairing of bases i.e. formation of a bond, takes place by two-step de-excitations. This translates to the interaction Hamiltonian acting twice on a state, giving us $\phi^2 = -1$, which fits our description of Ub. During the pairing process the energy quanta and the bases' states remain entangled.

Using $\Delta E_H \approx$ 7kT (as known from literature) we get $\exp(-\Delta E_H/kT) \sim 10^{-3}$ which is the order of observed error in DNA replication. Further, this mechanism allows only certain base pairs to spend time t_b close to each other. Using the uncertainty principle gives:

$$\Delta E_H t_b \approx \hbar \;\Rightarrow\; t_b \approx 4\times10^{-15}\ \text{sec}$$

Essentially what happens is this: the system, initially in equilibrium floats around till two pairing bases meet each-other. Thereafter they interact, entangle and whatnot such that we get an interaction Hamiltonian disturbing the equilibrium for a short time t_b . Beyond this, the interaction ends and the system tries to return to equilibrium.

Damped oscillations?

Observations tell us that the oscillation between the state $U_b\,|s\rangle$ and $-U_sU_b\,|s\rangle$ states is like a damped oscillator (with some time scale t_r) as shown in figure.

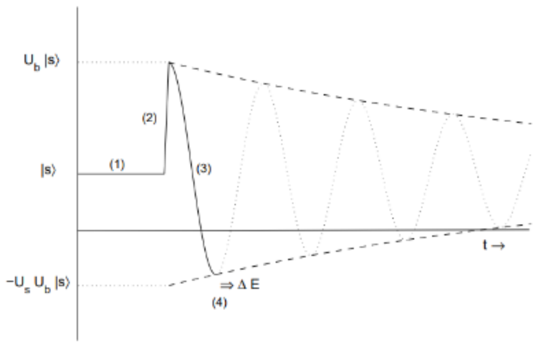


Figure 3: Time scales in DNA replication

Is there some physical intuition for this? Yes! Consider the ammonia NH_3 molecule. Due to quantum tunneling, the lone pair on Nitrogen atom can be above hydrogen or below it. In reality, it exists with a symmetric superposition of two as an equilibrium state. These two states are distinguished by their dipole moment, so If we apply an electric field, this pair stays in one of the states according to the field. But, as soon as the field is switched off, it oscillates between two states and slowly attains an equilibrium state. This is what the system described above is trying to do.

Photosynthesis

Another unexpected place Grover's algorithm is expected to show up is in photosynthesis! Generally a solar panel's efficiency is 10-20%. However plants have efficiencies of ≈95-99% during photosynthesis. How?! Here are a few theories:

Classical Hopping Theory

Traditional hopping theory in photosynthesis, also known as Förster resonance energy transfer (FRET), describes energy transfer between pigment molecules as a series of random ``hops." On absorbing light a pigment molecule gets excited and transfers energy to neighboring molecules through dipole-dipole interactions. Essentially energy movies towards a reaction centre where it is used for chemical reactions.

However, way lesser efficiencies than observed! The high efficiency in photosynthesis prompted quantum coherence and search algorithms to be significant instead of random hopping.

Quantum Coherence

The randomized energy transfer assumed in FRET somewhat prevents oscillatory dynamics.

So it was postulated that maybe the wavelike behavior of electrons being involved in the energy transfer mentioned above, In 2007 the U.S. Department of Energy's Berkeley Lab and UC Berkeley obtained the first direct evidence that remarkably long-lived wavelike electronic quantum coherence plays an important part in energy transfer processes.

Graham Fleming, the principal investigator for the study. "This wavelike characteristic can explain the extreme efficiency of the energy transfer because it enables the system to simultaneously sample all the potential energy pathways and choose the most efficient one."

Applying Grover

Weird as it sounds, we can model photosynthesis as a unsorted data search problem and use quantum algorithms to find solutions! Here's how:

- Superposition: We create a quantum superposition of all possible energy transfer pathways (states). This means that the quantum system explores multiple pathways simultaneously.
- Oracle Query: Use a quantum oracle to identify and mark the states (pathways) that represent high efficiency or optimal energy transfer. This could be implemented by evaluating each pathway's efficiency and adjusting the amplitudes of the quantum states accordingly.
- Amplitude Amplification: Apply amplitude amplification to increase the probability of measuring the optimal pathway. This involves quantum operations that enhance the probability of the efficient pathways while suppressing the less efficient ones.
- Measurement: Finally, measure the quantum state to collapse it to one of the optimal pathways, which represents the most efficient energy transfer configuration.

And this seems to work! Indeed, quantum algorithms can be seen to show up in many unexpected areas of research in novel ways. All we need to do is reduce something to an unsorted data search problem. Maslow worded it best: "If the only tool you have is a hammer, it is tempting to treat everything as if it were a nail."

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Interlude

2025, The International Year of Quantum Science and Technology

unesco

INTERNATIONAL YEAR OF
Quantum Science
and Technology

100 years of quantum is just the beginning...

On June 7, 2024, the United Nations proclaimed 2025 as the International Year of Quantum Science and Technology (IYQ). According to the proclamation, this year-long, worldwide initiative will "be observed through activities at all levels aimed at increasing public awareness of the importance of quantum science and applications."

The year 2025 was chosen for this International Year as it recognizes 100 years since the initial development of quantum mechanics. Join us in engaging with quantum science and technology education and celebration throughout 2025!

The above is a snapshot of the homepage of the internation year of quantum science and technology, as proclaimed by the United Nations. Quantum science, in its current state, is rapidly evolving into a field with extensive potential and brings with itself, the promise of an optimized future. Visit the website to learn more about the UN's declaration.

quantum2025.org

FROM CHAOS TO ORDER

The Eigenstate Thermalization Hypothesis

By Abhirup Mukherjee, Gluon

Thermalization in Classical Systems: Irreversibility and Role of Temperature

Placing a large number N of oxygen molecules in one corner of an isolated box leads to the question: What will the final speed distribution of the molecules be? The answer is, to a very good approximation, the Maxwell-Boltzmann distribution function:

$$f(v) = \left(\frac{m}{2\pi k_B T}\right)^{\frac{3}{2}} \exp\left(-\frac{mv^2}{2k_B T}\right)$$

where m is the mass of each molecule, k_B is the Boltzmann constant and T is the temperature of the system, fixed by the total energy U through the equipartition theorem $U = \frac{3}{2}Nk_BT$. This is one example of the power of statistical thermodynamics: given only the macroscopic parameter T it allows the calculation of average quantities to very high accuracies. This experiment is shown in Figure 1.

It is useful to examine some qualitative features of this solution:

- The Maxwell-Boltzmann distribution is independent of the initial conditions, except through the total energy U. No matter how the molecules are initially setup, time evolution ensures that they end up in the same distribution.
- The time evolution is irreversible. Even if all the molecules start out with identical speeds, they will almost certainly end up with speeds that are distributed at differing values, according to the above-mentioned distribution.

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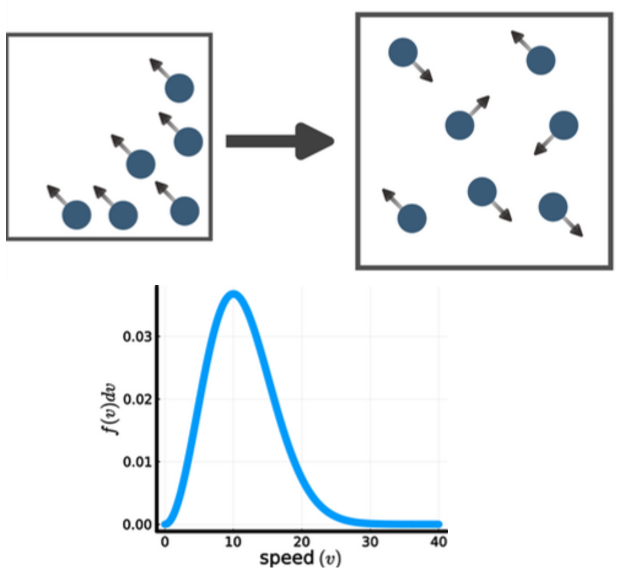


Figure 1: Molecules kept at the corner of a box in an orderly fashion gradually get their speeds distributed according to the Maxwell-Boltzmann distribution (bottom panel).

Within the formulation of statistical mechanics, they are explained using the ergodic hypothesis: given enough time, each molecule explores the entirety of its available phase space, and in doing so, the measured value is equal to the average within the patch of phase space at the appropriate energy [1, 2].

Can Quantum Systems Thermalize?

While this explanation makes sense from a classical standpoint, it is hugely problematic for quantum evolution. Given a system of N particles with a many-particle wavefunction $|\Psi(0)\rangle$ described by a Hamiltonian $\mathcal{H}$ the state of the system a later time t, is given by (setting $\hbar$ to 1): (see next page)

$$|\Psi(t)\rangle = \exp\left(-i\mathcal{H}t\right)|\Psi(0)\rangle$$

Both of the qualitative features mentioned in the previous section are absent in quantum time evolution: the evolution is time-reversible, and the final state depends on the details of the initial state. This is easily demonstrated by a simple model.

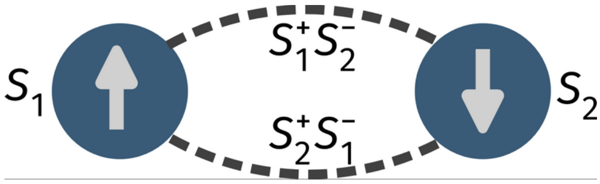


Figure 2: Systems of two spins. They interact with each other through spin-flip processes

Consider two spins interacting with each other through simultaneous flips; if one flips down, the other must flip up, and vice versa (Figure 2). The operator for an up(down) flip is S^+ (S^-) , so the Hamiltonian describing this process is:

$$\mathcal{H} = S_1^+ S_2^- + S_2^+ S_1^-$$

The first term flips the first spin up and the second spin down, while the second term does the opposite. We perform two parallel time evolution calculations, one with the initial state $|\Psi(0)\rangle = |\uparrow,\downarrow\rangle$ (red curve in Figure 3, and another with the initial state $|\downarrow,\uparrow\rangle$ (orange curve). For both the cases, we calculate the time evolution of the z-component of the first spin, defined as $\langle\Psi(t)|S_1^z|\Psi(t)\rangle$ with S_1^z being the z-component of the first spin. The results are shown in Figure 3, and we can draw the following conclusions:

- The time evolution does depend on initial conditions. The curve that starts from the $|\uparrow,\downarrow\rangle$ state does not in general match with the curve that starts from the $|\downarrow,\uparrow\rangle$ state.
- The evolution is reversible; the initial values are recovered at every 8th time step. This reversibility is also encoded in the fact that the evolution is unitary and all information is preserved in the process.

The challenge then, is : If we expect our universe to be fundamentally quantum, how do we reconcile these two features with those of thermalization.

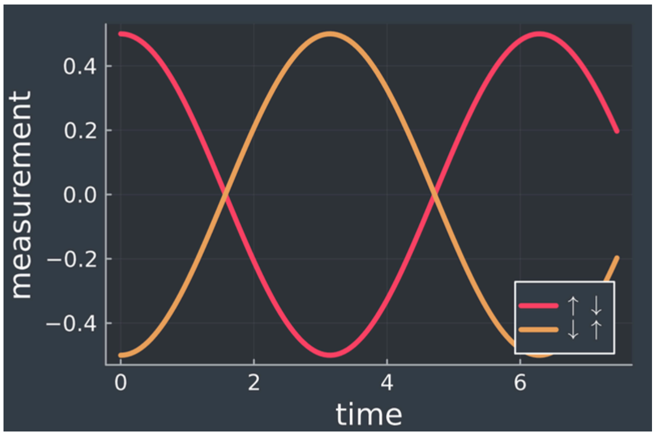


Figure 3: Time evolution of the average spin along z-direction for the first spin. The red curve is for an initial state where the first spin is up and the second one is down, while the orange curve starts with a flipped initial state. This evolution results from applying the operator exp(-iHt) to the initial state.

More specifically, how can unitary quantum evolution lead to a thermal state that has no memory of the initial state and that is in accordance with the predictions of thermodynamics?

The Eigenstate Thermalization Hypothesis

In the late twentieth century, the eigenstate thermalization hypothesis (ETH) was proposed as a solution to the above question [3, 4]. It is an ansatz for the matrix elements of operators $\mathcal{O}$ in the eigenbasis $\{|n\rangle\}$ of the Hamiltonian:

$$\mathcal{O}_{mn} = \mathcal{O}(\bar{E})\delta_{m,n} + e^{-S(\bar{E})/2} f_{\mathcal{O}} R_{mn}$$

While the ansatz may appear intimidating, its essence is straightforward: It says that given an observable $\mathcal{O}$ that can be measured in a laboratory, its matrix elements $\mathcal{O}_{mn} = \langle m|\mathcal{O}|n\rangle$ in the eigenbasis of the Hamiltonian is equal to the microcanonical expectation value $\mathcal{O}(\bar{E})$ at the average energy $\bar{E} = (E_m + E_n)/2$ if m=n, and it obtains corrections that are exponentially suppressed by the entropy S. Since S is extensive, these corrections vanish in the thermodynamic limit $N \to \infty$. This ansatz, of course, immediately explains the thermal behaviour of statistical mechanics, almost as a matter of principle, because in any eigenstate ($|m\rangle$ of the system at energy E_m expectation value of the operator will be, to a very good approximation, O(E), $\mathcal{O}(\bar{E})$ h is the expected value.

More importantly, we should analyse what this means for the mechanism of thermalization in quantum systems. The ETH tells us that quantum systems thermalize locally; even though the evolution of the total system is reversible and dependent on the initial conditions, the temporal behaviour of any small subsystem (a single particle, a single point in space, etc) becomes incoherent very fast. This happens because the information of the initial configuration of any individual particle gets scrambled through interactions with a macroscopic number of particles. This also explains the title of the article: multiple initial states (chaos) lead to the same value of the local observable (order)[5].

Quantum Thermalization in Action

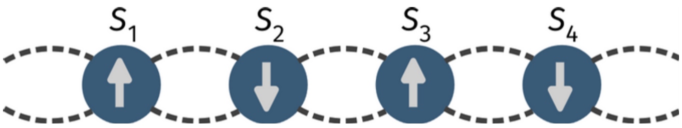
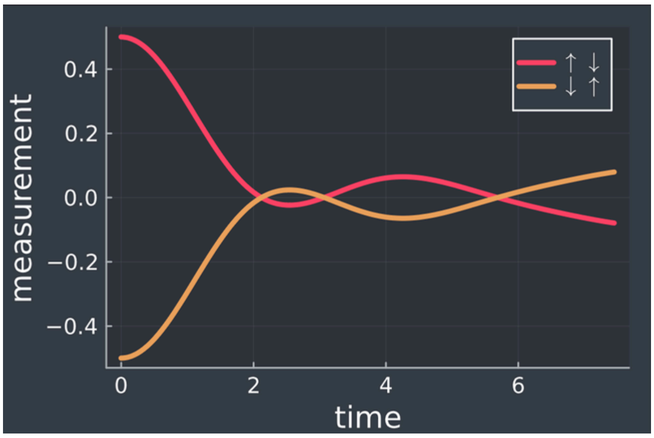


Figure 4: Model of several interacting spins. Each spin interacts with the two spins on each side of itself, through coordinated spin-flips.

The gist of the previous section was that quantum systems thermalize through interactions with other particles. This also explains why we did not see thermalization in Figure 2 - there were not enough interacting spins present to allow local information to scramble! To observe information scrambling as the number of spins are increased, we perform the same computations but now for N = 8 and N = 14 spins, for similar kind of Hamiltonians (each spin interacts with its neighbouring spins through spin-flips). The model is shown in Figure 4.

The results are shown in Figure 5, and the effect of increasing number of spins is quite apparent! Compared to the case of N = 2 (shown in Figure 2), the long-time evolution of both the initial states are approaching similar values, and the effect is more pronounced for N = 14 than for N = 8. This demonstrates how local measurements on a many-particle system display the loss of initial state memory (both the initial states approach similar values as $t \to \infty$ as well as the emergence of irreversibility (the oscillations get suppressed).



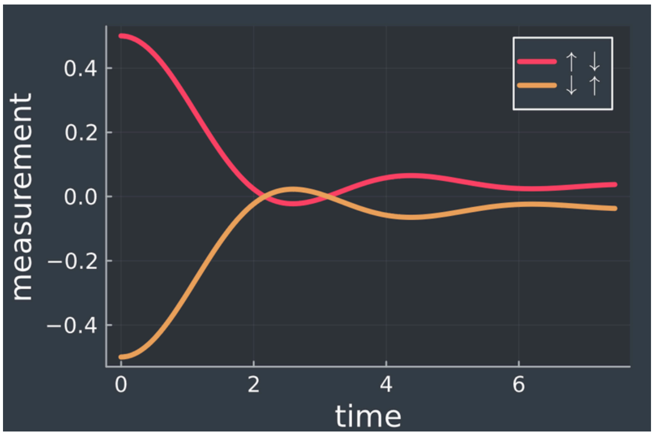


Figure 5: Evolution of expectation value of z-component of first spin for N = 8 spins (above) and N = 14 spins (below). As N is increased, the values better thermalize to common values.

Looking Beyond

It should now be clear from the above discussion that the thermalization we observe around us (and that are in agreement with statistical thermodynamics) likely results, more fundamentally, from the quantum interactions between system and universe. This is expressed formally by the ETH, and is demonstrated in Figure 5. While there is yet no derivation of the ETH, it has been tested on various systems and has proven to be quite successful. Heuristic justifications of the ETH come from random matrix theory (RMT): it can be proved that eigenvectors of random matrices satisfy an equation similar to the ETH equation, and the leap from RMT to quantum mechanics is then made by saying that interacting systems of a large number of particles are sufficiently complicated so as to be well-represented by random matrices. On the frontier, research is being carried out on exotic systems that violate the hypothesis (and hence the predictions of statistical mechanics) [6]. Researchers are investigating fundamental open questions such as the relation between ETH and entanglement.

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An *OUSUM(S)* Lab

1

An interview with Professor Akshay Singh of the Physics Department, IISc Bangalore

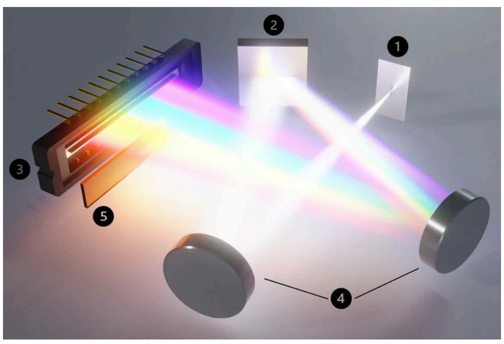
By Ritabrata Ghosh, Sachin Ghongde, Ensemble

You are a part of the OUSUMS lab. Could you please give us an overview of the primary research and experimental work that goes on in the group ?

OUSUMS lab basically stands for Optical Ultrafast Spectroscopy Understanding Material Synthesis. This comes from my PhD, where I did Optical Spectroscopy and PostDoc, where I did Synthesis and I realized you need to do both in the same lab to actually make progress; to understand the physics underlying and to get the actual properties which are hidden sometimes by defects. But, what we realized very quickly, was that not always are the defects bad. So this sort of brought us to the question: If defects are useful, should you still call them defects? This is something we've talked about a lot.

We mostly focus on two dimensional materials in our lab and right now, 90 percent of our work is on two-dimensional semiconductors. You can think of these two dimensional materials as sheets of paper. Between the layers of these 2D materials, there's Van Der Waals bond, whereas in there plane, there's covalent bonding. This means that you can actually stack many 2D materials on top of each other. And sometimes even a single layer can be stable at room temperature, cold temperatures or maybe elevated temperatures. This makes it quite interesting for a lot of new physics that comes in because you can now stack materials on top of each other. With these 2D materials, a lot of work has already been done for single layers. Also recently, a lot of the new things are coming out based out of hetero-structures.

In lab, we work a lot using Optical Spectroscopy. We use lasers, normal thermal light to measure luminescence and to do absorption spectroscopy.



A representation of optical spectroscopy.

From these measurements, we can understand not just the band gaps and what wavelengths these material do luminescence at, but also the interactions in these materials. In these materials there are things called excitons. You can think of an exciton as an electron and a hole bounded together. We measure these again with optical spectroscopy. Moreover, we synthesize some of these materials from scratch. Our main focus is to understand how exactly this synthesis is happening, how on an atomic scale these things are coming together and reacting, forming extended objects. We also see what kind of symmetries of the substrate play a role in guiding the growth of 2D material on top.

Cleary, research at this scale demands collaborations. How important do you think collaboration within the Institute, and with other institutes, is?

Let's say that you want to understand some scientific problem, so now, you can attack it at various levels, right? You can go to the basic level or you can say, 'okay, I have some background knowledge, so I will attack it at this level' or 'I have some advanced knowledge, I can attack it at this level.' Similarly for any scientific problem, you can say, "Since my lab has this particular expertise, I can attack these particular problems in certain ways."

If I'm really interested in a problem, I can develop in-house expertise. I can do some sort of a cost and benefit analysis in terms of time, resources and materials because it gives us this benefit of understanding. A lot of people actually do not grow their own materials, they rely on other people to grow materials. That's fine. It's completely fine because that gives them the time to work on the physics aspects without thinking about these other things. So really the question becomes what is the scientific problem you're trying to attack?

So if your problem is more of a fundamental level, for example, in our lab we work on things called, Single Photon Emitters. Thermal sources like sunlight or tube-light give you many photons at a time, even if you reduce the intensity. You will sometimes get only one photon, but other times, two photons or sometimes maybe five or so. It's a distribution! Whereas for a single photon source, you constrain it to only give you one photon.

It cannot give you any more. That's the source we want for some Quantum Communication and Computing. So essentially this is how you collaborate: one person can focus on creation of these single photon emitters, one person can work on the integration of these things. One person can create the photonic chip, another person can create the material for the photonic chip. We want to break up the problem into these chunks such that individual people and labs can actually attack to their highest capability rather than one person trying to develop all of this on their own. That's how these large large-scale collaborations work. The trick is to bring the experts and resources together, instead of reinventing the wheel on your own. So, for example, there's the National Quantum Mission (NQM). The main idea is not only that you want to spread the resources but it’s also to get the expertise from different labs, different people, And this is what we have done as well. So for single photon emitters, we have teams from IIT Delhi, Jain University in Bangalore. IIT Madras is there then for the Photonic Quantum Computing. We have teams from CDAC, which is a government lab in Bangalore.

> “The trick is to bring the experts and resources together, instead of reinventing the wheel on your own.”

What’s your mentoring philosophy, and what drives research in the lab? How could an undergrad expect to contribute to the research?

Personally, I feel that under my mentoring, if you're not motivated, and if you're not self-driven, you will probably not be able to do much in the lab. You can just go along, but you will not be able to do much thinking because usually I want the students to take initiative to come up with their own solutions to the problem. I'm there with you, to advise you. But I'm not going to go in and sit with you, for hours trying to figure out a problem. Its okay for the students to remain stuck on some problem for a few days. Its okay to struggle for it. Struggling through it is part of the training process.

It took us some time, but we now have this idea that we just straight away pair an undergrad with a graduate student mentor, because they can work, day-in and day-out with this person. Now how does any further work happen? So let’s say we are working on something like 2D materials. If I take the most recent example, we had almost 5 summer interns, for 2 months. What aspects of the problem could be attacked by these interns in some 2 months is something that we discussed a while ago with the graduate students. So under 2D materials, on the growth part, we said, ‘okay, can they work on the transfer?’ It’s grown on a substrate. Now, the optimization part takes some time. So we said, ‘okay, let's have a student on this thing’. But it can become tedious working in the lab. Also, you simply can't from start working in the lab from day one! So to all of them we gave a coding or instrumentation project. Here’s a problem they worked on: “What type of microstructures develop in these 2D samples?” We observe triangular growth patterns. Then, what you want is an aligned triangular group. That means, if you draw a line on the substrate, all of the triangles should be pointing along that line. You can make the system do that. But some triangles don't want to do that! They misalign! So now the problem is, we want to quantify the amount of triangles that are aligned. This can be done using some machine learning, algorithms and image analysis algorithms. One of the undergraduates from one of the IISERs was actually able to finish a large part of the code. And obviously, if we use that code and that analysis later on, they will be part of that paper. So we asked all interested students to actually continue, in a remote capacity. So this past year, we’ve already had a publication where the undergrad summer intern from one of the IISERs did a major part of the work. So basically, we try to break up the problems into chunks as to who can access which part of the problem.

> “Struggling through it is part of the training process.”

A major issue of research, I believe, is that there too many problems out there which require to be studied. How do you shortlist problems to focus on?

I think of it like a Venn diagram. You have a certain set of problems in the real world, and you have expertise in certain fields. What you have to look at is the intersection of these two. You don't want to get into things, which you're not an expert on, because it's going to take a an excessive amount of time. But there can be certain instances when there are problems that excite you. To give an example, for the past one and a half years, we've started working on two-dimensional magnetism. This is something that I have been interested in for the past few years. Once you've started working on a problem, you eventually starts to peel off its various layers. For example, let's say I am in interested in how fluid flow changes our synthesis process dramatically. So to understand that, we must delve into laminar flows, turbulent flows and whatnot.
So essentially, whenever you attack a problem there can be a variety of directions you can take. But it is extremely important to realize that, outright, there is neither a right path nor a wrong one when digging through a problem.
Then it is also important that your students are interested in the problem at hand. At the end of the day, they are going to be working on it in the lab as well! Another challenge that we experimentalists often face involves resource and capital constraints. You always have a certain pot of money that you can work with. So for instance you may want to do this really cool experiment, but it involves a magnetic field at low temperatures like some milli-Kelvin or so. If you don't have that equipment, you simply can't work on it unless you find a collaborator. But that's how life goes. You have deal with constraints and find the optimal solution ahead.

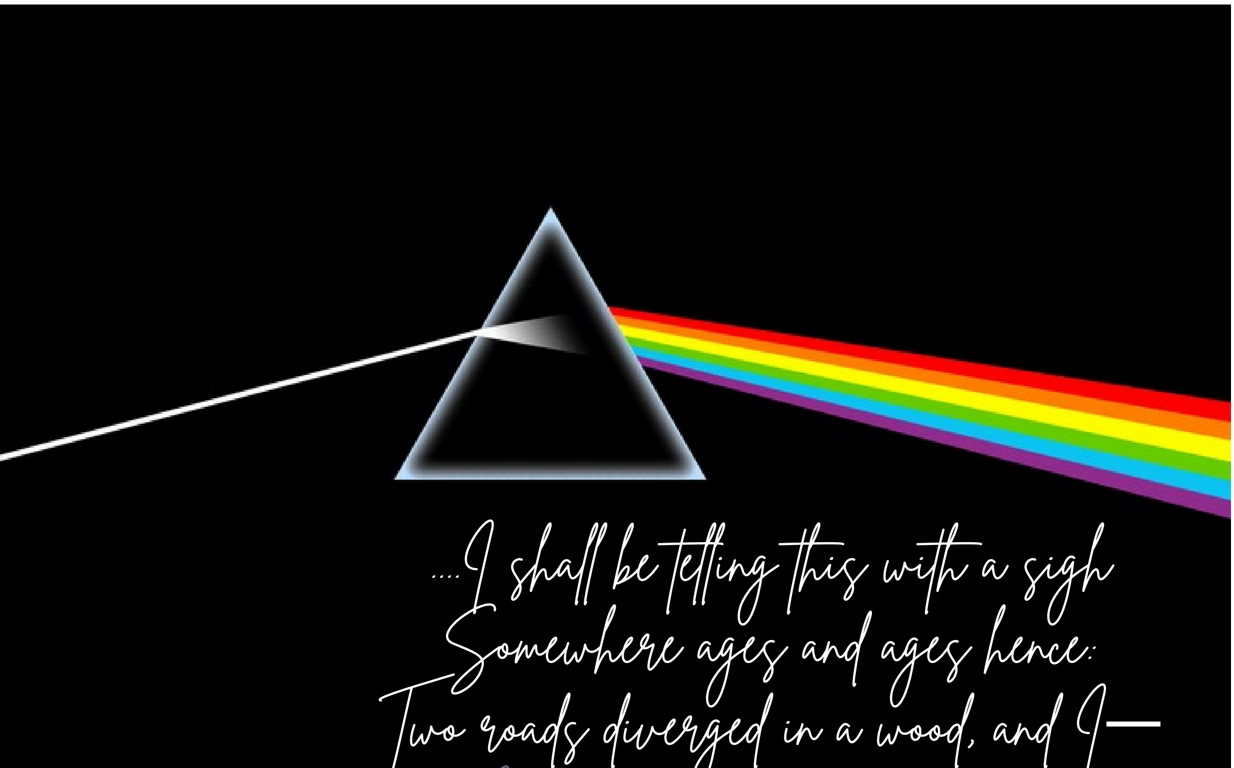
"......there is neither a right path nor a wrong one when digging through a problem."

15-12-2022: Dr. Archana Raja (Staff Scientist, Berkeley Lab) visits Professor Akshay Singh's lab.

Bose Einstein Statistics Centenary Special:

PHOTON BUNCHING AND BOSE EINSTEIN STATISTICS

By Adityadhar Dwivedi, Phi@I



....I shall be telling this with a sigh
Somewhere ages and ages hence:
Two roads diverged in a wood, and I—
I took the one less traveled by,
And that has made all the difference.

Robert Frost

Have you ever wondered, how we differentiate the smallest of quanta from each other? Like, aren't they all the same? Well, somewhat yes, but when you talk about them in terms of their degrees of freedom, like their energy, momentum, angular momentum etc., they show a very peculiar property. Join us in this exciting adventure of finding secrets about our "favourite boson" aka photons?.

Bunching of paths imposed by "friends"

Has it ever happened to you that while you're returning back from classes to have lunch, you meet with a friend who is also as confused as you, as to which mess they should eat at today. So you guys happen to choose your paths "collectively'' this time. However on a regular lonely day, you'd have chosen a totally random mess to eat?

Well this same analogy can capture how 2 photons of matching degrees of freedom happen to "take" decision "collectively" as to which path to choose. When they were "strangers" to each other, they were altogether going random pathways but when their degrees of freedom match, they happen to "bunch" around to any random path.

Well, this phenomenon is called Bunching!

With the centenary of Bose Einstein Statistics, we would embark on journey of photon statistics of how they come to show Bose Einstein Statistic when they are ``bunched'' and discrete Poissonian statistics when they are completely distinguishable!

Generalised Particle Statistics

Distinguishability and Indistinguishability of particles have got its applications in many fields of current research like quantum metrology, quantum computing etc. Generally, statistical distribution of particles can be described as

$$P_\epsilon = \frac{1}{e^{\frac{\epsilon}{k_B T}} - S}$$

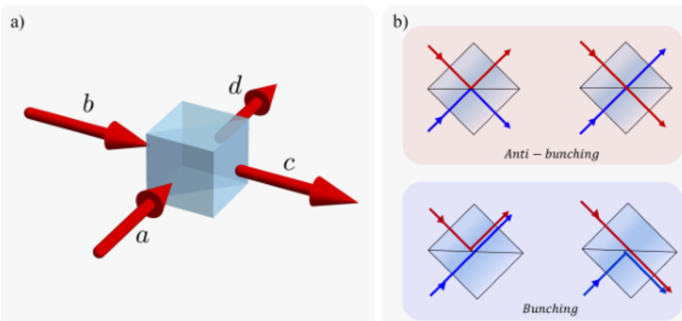
where ϵ represents energy, k_B represents Boltzmann's Constant and T is absolute temperature. [1]
For indistinguishable fermions (particle with half integer spins) P_ϵ represents Fermi Dirac Statistics with S=-1 while for boson (particle with integer spins), it shows Bose Einstein Statistics with S=1. You can wonder, what is S then, how does S vary?

En route to mess at H5 or H7 @ IISERM

Hong Ou Mandel Inerferometer

Remember the analogy of 2 friends going to mess to eat collectively together? Well, replace them with photons now, voila! Here is your Hong Ou Mandel Interferometer}!! Ta-da!

Excited? No, because I have really skipped a lot of nuances to fill in, right? So, starting with definition: Hong Ou Mandel (HOM) Interferometery is a two photon interference in which we test distinguishability of two photons of several degrees of freedom (e.g. spatial time delay τ , frequency ν etc.,), by injecting them into two input ports (paths 1 and 2) of 50/50 beamsplitter with exactly same DOFs such that the two photon pairs (under correct resolution) follow only one path at a time i.e either path 3 or 4 together.



a) A balanced beam splitter with input ports designated a and b, and output ports designated c and d. (b) Four possibilities of interaction of two photons at the input ports of BS.

This non classical bunching phenomenon can be explained by Symmetrization postulate and Spin statistics theorem. [1]
The symmetrization postulate states that the wavefunction of a system of identical particles must be either symmetric or antisymmetric under the exchange of any two particles. For two particle system,

$$|\chi_1, \chi_2\rangle = e^{i\phi_{ex}}|\chi_2, \chi_1\rangle$$

where particle exchange phase ϕ_{ex} is zero for bosons and π for fermions.

Distinguishability and Indistinguishability (by transform pulses)

Generally, indistinguishability of photons comes from entanglement with outer system. However, in some cases like in SPDC process, property of entanglement can be achieved back through phase matching condition!

In frequency degree of freedom (i.e, photon can have different energies) photon state is a mixed state of transform-limited* pulses with different center frequencies.

For a pulse to be transform limited, relation between duration of pulse and range of frequencies a single photon contains, is at its theoretical minimum. So, broader the range of frequencies (also energies), the shorter the pulse duration.

A transform limited pulse ensures the photon temporal profile is "tighest" minimizing any uncertainty in arrival time!

$$|\omega\rangle = \int_{-\infty}^{+\infty} dv g_\omega(v) a^\dagger(v)|vac\rangle$$

where $a^\dagger(v)$ is the single photon creation operator, $|g(v)|^2$ is the spectrum of transform limited pulse with center frequency ω and width Δ_g (intrinsic width). Considering interaction of external environment is similar during photon generation so width of other independent transform limited pulses, say $|\omega_j\rangle$, same.

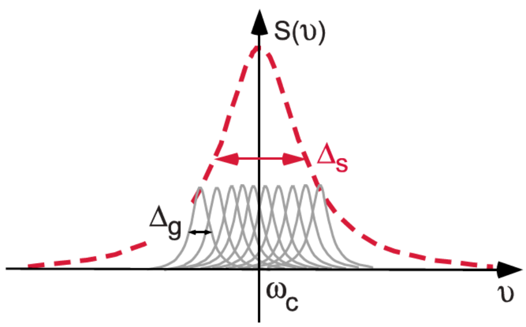


Illustration of total single photon pulse (red dashed curve, width Δ_s) composed of transform-limited pulses (grey bold curves, width Δ_g) [2]

Therefore, indistinguishability as we know of it is related to identicality of these separate transform limited pulses. Indistinguishability of 2 independent transform-limited pulse is

$$K_{ij}^{TL} = |\langle \omega_i | \omega_j \rangle|^2$$

i.e, when those photons are totally distinguishable when $|\omega_i \omega_j| \gg \Delta_g$
and indistinguishable for $\omega_i = \omega_j$ [2]

Also single photon may get entangled with outer environment thus center frequencies have the distribution $f(\omega)$ such that

$$\int_{-\infty}^{+\infty} d\omega f(\omega) = 1$$

with extrinsic width Δ_f . State of photon could be written as:

$$\rho = \int_{-\infty}^{+\infty} d\omega f(\omega) |\omega\rangle\langle\omega|$$

The total spectrum

$$S(v) = \int_{-\infty}^{+\infty} d\omega f(\omega) |\omega\rangle\langle\omega|$$

is broadened to $\Delta_s \geq \Delta_g$ because of distribution $f(\omega)$. From figure 3, when $\Delta_s = \Delta_g$ is satisfied single photon pulse become transform limited and "indistinguishable".
For two photons, the indistinguishability of two independent single photons can be described as

$$K = tr(\rho \otimes \rho) = \int\int_{-\infty}^{+\infty} d\omega_i d\omega_j f(\omega_i) f(\omega_j) |\langle \omega_i | \omega_j \rangle|^2$$

When state ρ is a pure state i..e, it does not entangle with outer environment i.e $\Delta_f = 0$ and $\Delta_s = \Delta_g$, K becomes 1 and single photon states are indistinguishable! [2]

Extending it further.....

Consider a multi photon state from N separated emitters can be described as

$$\rho_{N\ photon} = C_0 \otimes_{k=1}^{N} (|vac\rangle\langle vac| + c_k \rho_k)$$

where each state ρ_k describes a quantum state of a single photon so $tr(\rho_k) = 1$, C_0 is a normalisation constant.
We take same assumption as before that all emitters are under same environment during photon generation process i.e, $c_k = c$ and $\rho_k = \rho$.

We define indistinguishability of n photons as $K_n = tr\rho^n$ where in our general analogy or normal HOM Interferometer, we would get concerned about two photon interference.

When both $f(\omega) = \dfrac{e^{-\frac{(\omega-\omega_c)^2}{2\sigma_f^2}}}{\sqrt{2\pi\sigma_f^2}}$ and $g_\omega(\nu) = \dfrac{e^{-\frac{(\nu-\omega)^2}{(2\pi\sigma_g^2)^4}}}{2\pi\sigma_f^2}$

are Gaussian function with widths σ_f and σ_g , respectively we can obtain $K = \dfrac{\sigma_g}{(\sqrt{\sigma_g + \sigma_f})}$

As before, equation 3 to find K_n we would have to calculate

$$K_{ij} = |\langle \omega_i | \omega_j \rangle|^2 = \int_{-\infty}^{+\infty} (g_{\omega_i}^*(v) g_{\omega_j}(v))^2 dv = e^{-\frac{(\omega_i-\omega_j)^2}{4\sigma_g^2}}$$

Integrate it over tensor product of n photon state of which elaborate calculation is given [Sun2017] [3] paper of which value of K_n can be tabulated as:

n	K_n
2	K
3	$\frac{4K^2}{3+K^2}$
4	$\frac{2K^3}{1+K^2}$
5	$\frac{16K^4}{5+10K^2+K^4}$
6	$\frac{16K^5}{3+10K^2+3K^2}$

Table 1: Multiphoton Indistinguishability with increasing number photon K being indistinguishability of 2 photon [3]

It was shown that value of K_n decays with increase in photon numbers. Also, it is well fitted by exponential decay rate of $\alpha(K)$ i.e,

$$K_n(K) = e^{-\alpha(K)n}$$

Because the nonzero K will induce phton bunching, the photon-number distribution strongly depends on value of $K_{n(n>1)}$.
Formally, the photon state can be written as:

$$\rho_{Nphoton} = C \sum_{n=0}^{N} \binom{N}{n} B_n c^n \{n\}$$

where C is a new normalization constant, {n} describes the state with the photon number of n, and B_n is an indistinguishability- $(K_{n(n>1)} > 0)$ induced photon-bunching coefficient.
Boson Permutation Symmetry induces photon bunching effect. As per permutation of n photons to obtain B_n of n photon state viz,

$$B_n = \sum_{k=2}^{n} D_{n,n-k} K_k + 1$$

where $D_{n,n-k} = \frac{n!}{(n-k)!}\sum_{i=2}^{k}\frac{(-1)^i}{i!}$
are Recontres Numbers which show number of permutations of n photons with (n-k) photons without permutations.

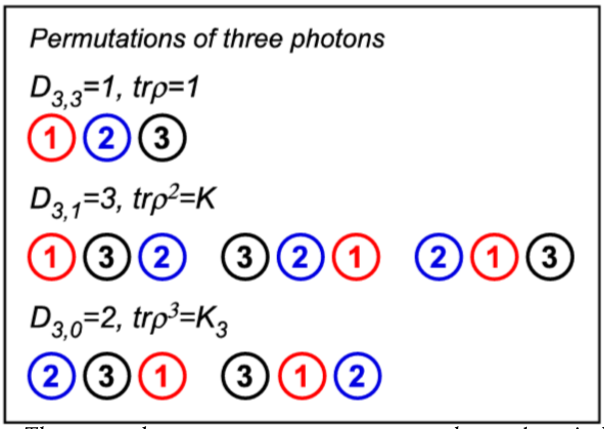


Fig: The way photon can permute among themselves induces bunching effect, thus a significant property of boson

In this way, Recontres Number are defined as number of derangements with k fixed points when $0 \le k \le n$. Derange all those point which are unfixed!

- For totally indistinguishable states, $K_n = 1$.

$$B_n = \sum_{k=2}^{n} D_{n,n-k} + 1 = n!$$

shows n photon-bunching result and $\{n\} = |n\rangle\langle n|$ is a n-photon Fock (Number) state.

- For totally distinguishable state with K=0, $K_n = 0$ and $B_n = 1$.
- For partially indistinguishable photons, $1 < B_n < n!$

When $n \gg 1$,

$$\frac{B_{n+1}(K)/(n+1)!}{B_n(K)/n!} \to \frac{K_{n+1}}{K_n} = e^{-\alpha(K)}$$

It shows that there is exponential decay rate of $\frac{B_n(K)}{n!}$ with decay rate of $\alpha(K)$. [3]

Signature of Bose Einstein Statistics while Bunching

- For distinguishable states, $B_n = 1$ photon bunching doesn't occur so they follow random path across different ports (as in case of beam splitter) i.e, $\rho_{Nphoton}$ show a classical state with a binomial distribution which converts to Poissonian distribution when $N \gg 1$.
- For all indistinguishable states $K_n = 1$ with and $B_n = n!$ photon number distribution is

31 $$\rho_{Nphoton} \simeq (1 - Nc)\sum_{n=0}^{N}(Nc)^n|n\rangle\langle n| = \sum_{n=0}^{N} P_n|n\rangle\langle n|$$

when Nc < 1 and $N \gg 1$. It can be described by Bose Einstein Statistics with

$$P_n = \frac{\bar{n}^n}{(1+\bar{n})^{n+1}} = P\frac{e^{-n\epsilon/k_BT}}{e^{\epsilon/k_BT} - 1}$$

where
$Nc = e^{-\epsilon/k_BT}, P = e^{\epsilon/k_BT} + e^{-\epsilon/k_BT} - 2$
and $\bar{n} = Nc/(1 - Nc) = 1/(e^{\epsilon/k_BT} - 1)$
is the mean photon number.

- However, for photons with partial indistinguishability $(0 < K_n < 1)$,the photon state should be

$$\rho_{Nphoton} \simeq (1 - Nce^{-\alpha(K)})\sum_{n=0}^{N}(Nce^{-\alpha(K)})^n|n\rangle\langle n| = \sum_{n=0}^{N} P_n(K)|n\rangle\langle n|$$

When Nc < 1 and $N \gg 1$, a modified Bose Einstein statistics can be represented as:

$$P_n(K) = P(K)\frac{e^{-n[\epsilon/k_BT + \alpha(K)]}}{e^{\epsilon/k_BT} - S}$$

where $P(K) = e^{\epsilon/k_BT} + e^{-\epsilon/k_BT - 2\alpha(K)} - 2e^{-\alpha(K)}$
and mean photon number is

$$\bar{n} = \frac{Nce^{-\alpha(K)}}{1 - Nce^{-\alpha(K)}} = \frac{1}{e^{\epsilon/k_BT + \alpha(K)} - 1}$$

and S is indistinguishability induced bunching factor. [3]

Statistical Transition during bunching

We apply second order correlation function $g^{(2)}(\tau)$ to probe photon statistical transition from Poissonian Statistics to Bose Einstein Statistics. What is exactly $g^{(2)}(\tau)$?

Suppose a Gaussian wavepacket of light with longitudinal spatial width σ is propagating in a given direction and another gaussian wavepacket of light with longitudinal spatial width σ having the same spectrum of frequencies is propagating in the same direction. The peak of the two gaussians is separated by a distance τ. As long as $\tau \gg \sigma$ a high degree of interference will occur.
If $\sigma \gg \tau$ a low degree of interference will occur. Maximum interference obviously occurs when $\tau = 0$, when the wavepackets have maximum overlap.

From single photon state, c is photon emission probability from an emitter and Nc is number of photons from N emitters without photon bunching.

- When $Nc \ll 1, g^2(0) = 1 + K$
- When $Nc \gg 1$ and $K > 0$, bunching effect dominates quantum statistics!

When $n \gg 1$, photons condense into n photon Fock (Number) state with $g^{(2)}(0) \to 1$.
We can infer behaviour of photon statistical transitions from $g^{(2)}(0) = 1 + K$ to $g^{(2)}(0) \to 1$ with an increase in photon number Nc. [3]

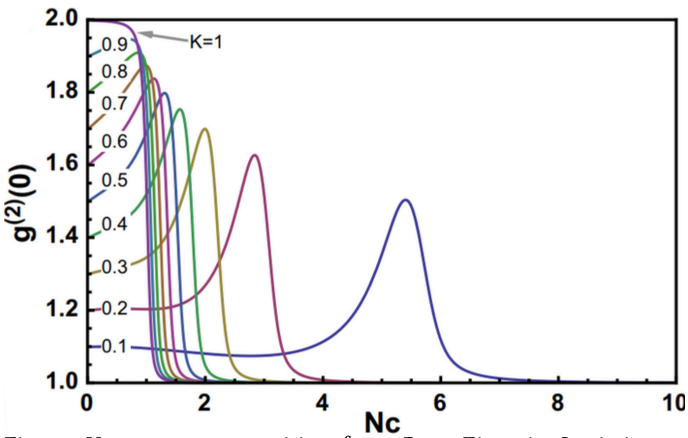


Figure: You can see transition from Bose Einstein Statistics to (usual) Poissonian Statistics of Laser light [3]

For an indistinguishable photon state with Bose-Einstein statistics, the transition occurs at Nc = 1. The transition is largely contributed indistinguishability induced bunching effect. [3]

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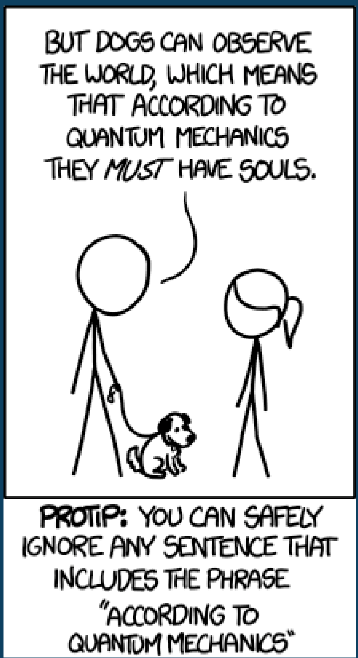
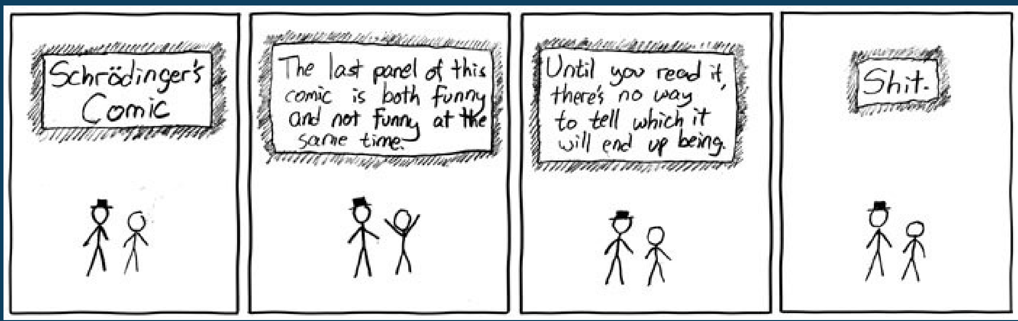
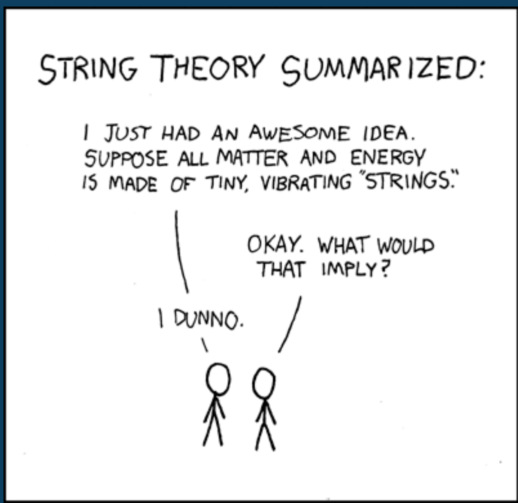
Interlude

Physics jokes from the Internet

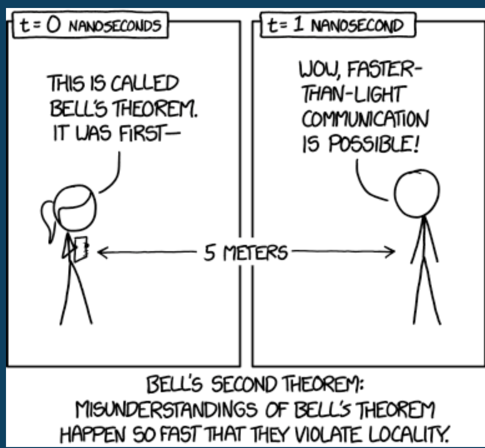
(not plagiarising, we have citations)





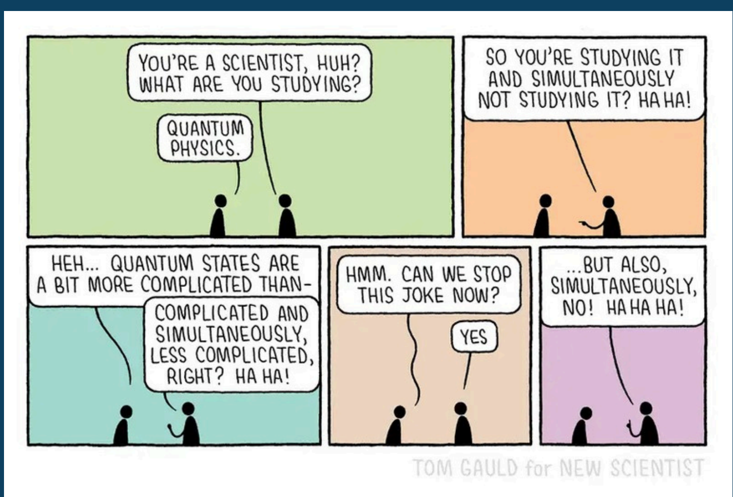


We love xkcd.

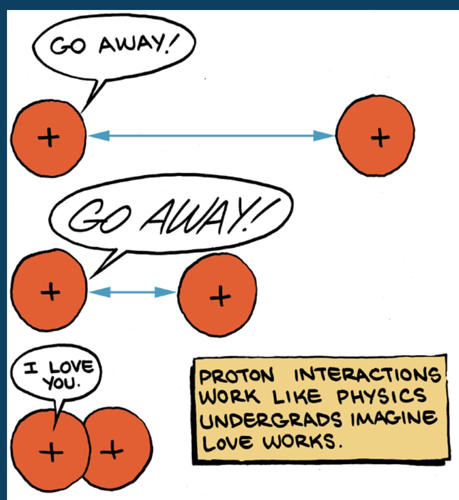


An electron and a positron go into a bar.
Positron: "You're round."
Electron: "Are you sure?"
Positron: "I'm positive."
Source: The Guardian

Google announced a major breakthrough in quantum computing. This is really great news. And at the same time, it's really bad news.
Source: Reddit



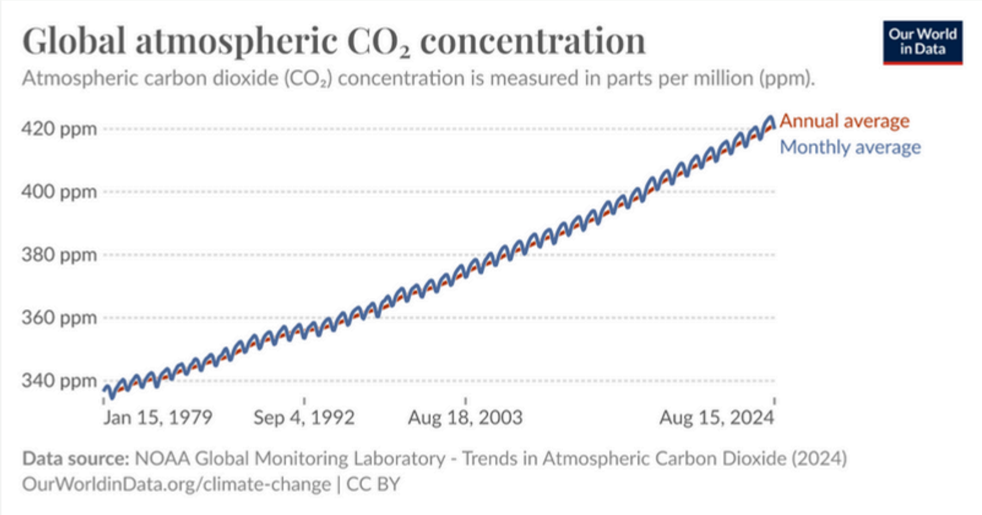
Sources:
(left) New Scientist
(right) The Finch and the Pea



Contact your local physics club to share any jokes you cook up!

CO_2, QUANTUM MECHANICS AND CLIMATE IMPACT

By
Alokparna Pal,
Jyotirmoy Dey,
IBPC



What exactly about CO2 makes the earth warmer? We take a look at quantum aspects of the structure of carbon dioxide and their implications on the environment.

Carbon dioxide (CO_2) is a crucial greenhouse gas present in the atmospheres of Venus, Earth, and Mars. Its ability to absorb infrared radiation makes it a key player in regulating planetary temperatures. While the scientific principles behind anthropogenic climate change are well-established, much of the understanding relies on empirical data from spectral absorption databases. However, the warming effect of CO_2 can also be understood from a first-principles perspective, rooted in the molecule's quantum mechanical properties, specifically its vibrational and rotational transitions.

CO_2 Molecular Structure and Vibrational Modes

CO_2 is a linear molecule consisting of a central carbon atom double-bonded to two oxygen atoms (O=C=O). This triatomic molecule has three degrees of freedom in rotational motion and six degrees of freedom in vibrational motion. The vibrational modes of CO_2 are crucial in determining its ability to absorb infrared radiation:

- Asymmetric Stretching (V_3 mode): In this mode, one oxygen atom moves towards the carbon atom while the other moves away. This movement alters the dipole moment of the molecule, enabling it to absorb infrared radiation effectively.
- Bending (V_2 mode, degenerate): The molecule bends in two perpendicular planes, leading to degenerate vibrational modes. Due to the symmetrical linear structure of CO_2, the potential and vibrational energies for these two bending modes are identical, resulting in their degeneracy.

These vibrational modes correspond to specific quantized energy levels, and the absorption of infrared (IR) radiation excites transitions between these levels. The energy of IR photons is sufficient to cause changes in the vibrational state of CO_2, making it an effective greenhouse gas.

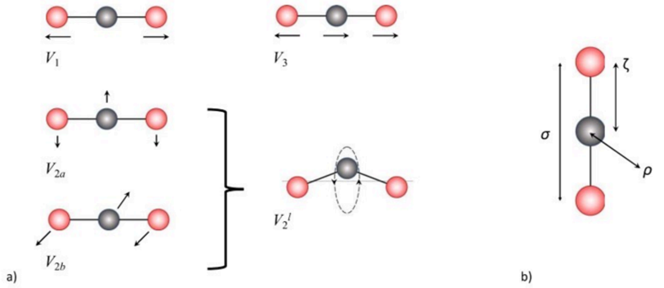


Figure 3. (a) Schematic of the three vibrational modes of carbon dioxide. The two degenerate bending modes superimpose to produce a motion where each atom rotates around the major axis of the molecule, which is represented via the quantum number l. (b) Mass-weighted coordinate system used to express the three fundamental modes of CO_2 as simple harmonic oscillations (see Section 4).

Rotational Transitions in CO_2

In addition to vibrational transitions, CO_2 also exhibits rotational transitions. For a linear molecule like CO_2, rotational energy levels are quantized according to the quantum number J, where J=0,1,2, ... Each vibrational state can have multiple rotational levels, leading to a combination of vibrational and rotational transitions when the molecule absorbs infrared radiation. This combination produces a spectrum known as the ro-vibrational spectrum.

The primary selection rule for rotational transitions is that the rotational quantum number can change by ±1 during a transition. For vibrational transitions, the selection rule is generally the same, although transitions with changes of ±2, ±3 are possible, albeit weaker.

Fermi resonance in CO_2

Fermi resonance is a quantum mechanical phenomenon where two vibrational modes of a molecule, close in energy, interact with each other. This interaction causes the two modes to "mix," resulting in a shift in their frequencies and an increase in the intensity of their absorption bands.

In CO_2, Fermi resonance occurs between the bending mode V2 (with an energy around 667 cm^{-1}) and a combination mode, usually the overtone of the bending vibration denoted as 2V2 (the first overtone of the bending vibration, theoretically close to 1334 cm^{-1}). The overtone 2V2 interacts with the asymmetric stretch V3 mode, which also has an energy close to that of the overtone. This interaction "mixes" the states, causing:

1. Frequency Shift: The frequencies of the interacting modes are pushed apart due to the resonance, leading to observed frequencies that differ from the unperturbed mode frequencies.
2. Intensity Redistribution: The absorption bands' intensity can be redistributed, meaning one band may become stronger while the other weakens, depending on the interaction.

This resonance increases CO_2's efficiency in absorbing infrared radiation, enhancing its greenhouse effect. As the Earth absorbs sunlight, it re-emits this energy as infrared radiation. Greenhouse gases like CO_2 trap some of this radiation in the atmosphere, preventing it from escaping into space and thereby warming the planet.

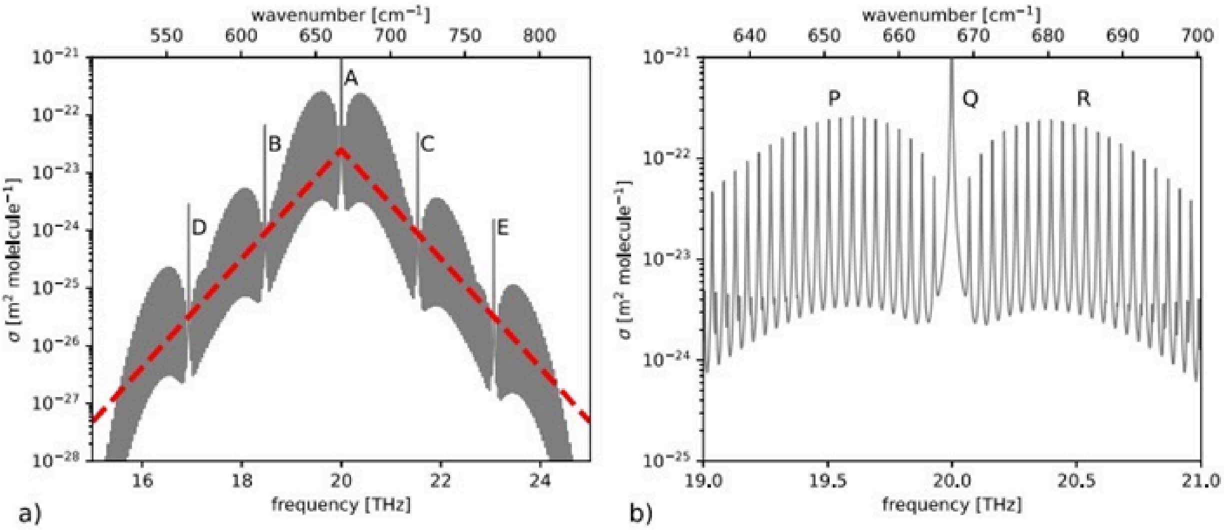


Figure 7. Analytic CO_2 ν_2 band, including the fundamental vibrational transition and four additional Fermi sidebands. The red line in panel (a) shows the approximate band shape predicted using Equations (3) and (35), given $T = T_s$. Labels in (a) correspond to the transitions in Figure 5. (b) shows a close-up of the fundamental band. Pressure and temperature are the same as in Figure 2.

Implications for climate science

The quantum mechanical basis of Fermi resonance in CO_2 provides a deeper understanding of its role in global warming. The interaction of vibrational modes in CO_2 is not random but a predictable and quantifiable event. This predictability allows scientists to model and understand CO_2's behavior in the atmosphere with greater accuracy, leading to more precise predictions about the impact of rising CO_2 levels on global temperatures. The enhanced greenhouse effect due to Fermi resonance means that as CO_2 concentrations in the atmosphere increase, the warming effect also intensifies. This creates a feedback loop where increased temperatures lead to further CO_2 emissions (e.g., from permafrost melt or increased respiration), which in turn leads to more warming.

Interdisciplinary Approaches to Global Warming

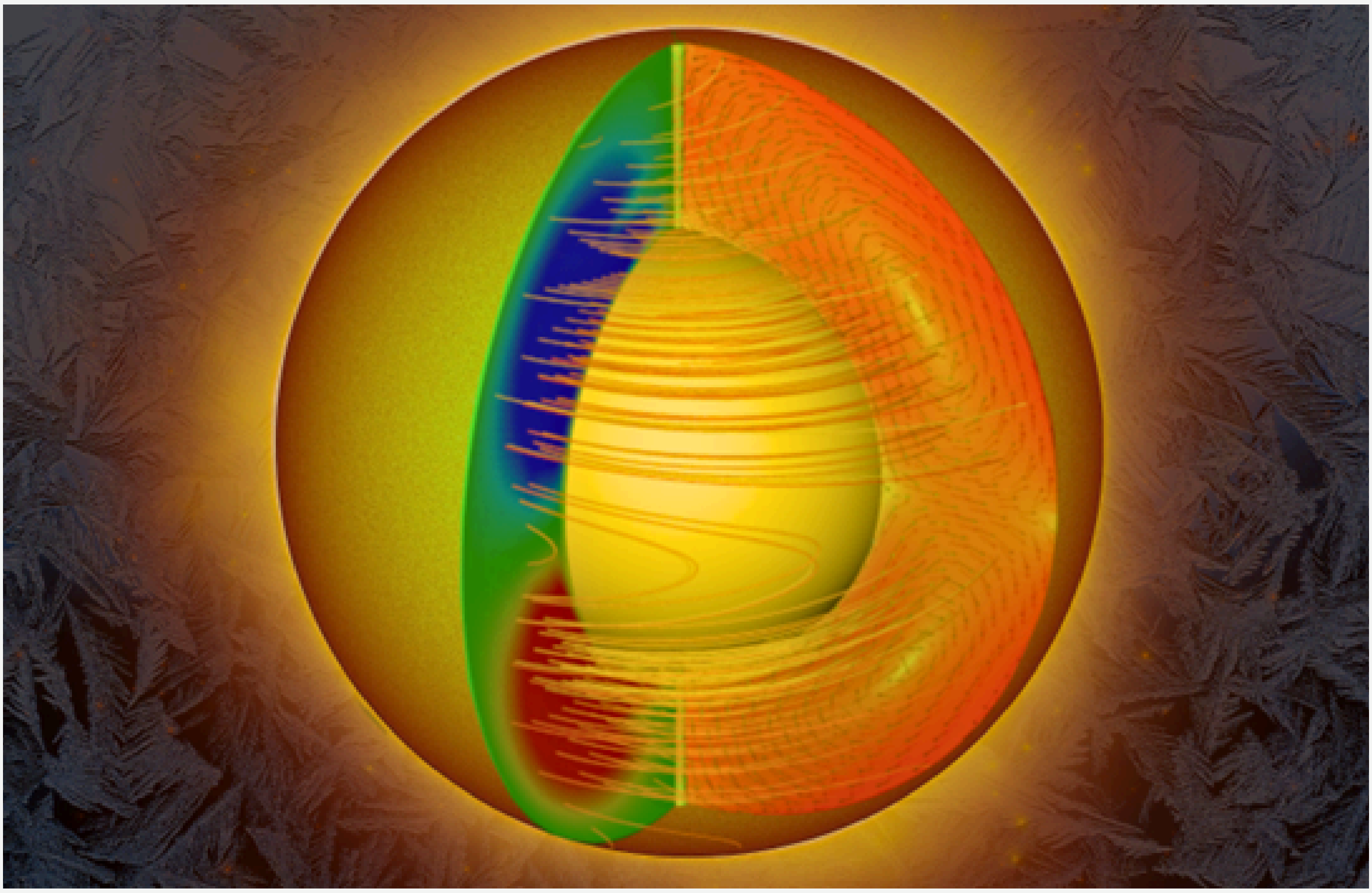
The quantum mechanical principles governing CO_2's molecular vibrations are essential for addressing global environmental challenges. These principles can also be applied to other greenhouse gases, such as methane or nitrous oxide, which have different but equally significant impacts on global warming. By highlighting the quantum mechanical basis of global warming, we emphasize the importance of interdisciplinary approaches that combine physics, chemistry, and environmental science.

In conclusion, solutions to global warming must be grounded in a thorough understanding of the fundamental processes driving it, rooted in the quantum mechanical interactions of molecules in the atmosphere. This understanding provides the foundation for more accurate climate models and more effective strategies to mitigate the impacts of climate change.

PEEPING INTO A SLEEPING SUN

The Solar Grand Minimum

By Chitradeep Saha, Gluon



An artistic impression of a ‘spotless’ Sun in a deep magnetic slumber and exposed up to its deep convective interior, on the backdrop of frozen ice crystals – signifying the influence it may have had on the global freezing of our planet Earth in the past. Image: Author

It was a world before Watt's invention of steam engines. Italy was thriving in the glow of the Renaissance. Stradivarius was shaping the most admired violins from dense maple woods of Northern Croatia, crafting timeless masterpieces. Modern astronomy was maturing with the advent of telescopes and Galileo counting the sunspots. While far in the East, China's Ming dynasty was faltering under erratic harvests. An apocalypse loomed large on the northern hemisphere as humanity stood on the edge of a new era – the Little Ice Age! By the late sixteenth century, global temperature plummeted so dramatically that Mediterranean harbours froze, birds tumbled from the sky, and London's Thames turned into a frozen merry land. "Frost fairs" sprang up on the ice – full of kiosks, taverns, and even brothels [1].

Contemporary astronomers were baffled by a new phenomenon in the sky – sunspots had all but vanished, disappearing for days, months, even decades! Later, astrophysicist John Eddy named this period of prolonged quiescence the Maunder Minimum, after the astronomers Edward Maunder and Annie Russell Maunder, who studied and recorded sunspots for long[2]. Some say sunspots did not entirely vanish during this period, rather telescopes were not good enough to 'see' the smaller ones back then. Today, it is well known that the changing number and size of sunspots on the Sun's surface is a telltale sign of its dynamic magnetic activity, which waxes and wanes on a decennial rhythm – called the sunspot cycle. Did this apparent cessation of the Sun's magnetic cycles have anything to do with the drastic cooling of our Earth? Well, that is a matter of debate and, more importantly, not a subject of our present story. What is more interesting from the perspective of a heliophysicist is to ask why the Sun slipped into a slumber, what all happened inside the sleeping star and how eventually it rose back to its full glory again?

Winter landscape with a windmill, painted in 1615 by a Dutch artist, Hendrick Avercamp. Image: Wikimedia Commons

Nature has preserved the Sun's magnetic history in cosmogenic isotopes like Beryllium-10 in polar ice cores and Carbon-14 in tree rings. When the Sun is magnetically active, faster solar wind sweeps away cosmic particles, reducing the deposition of these isotopes on Earth. Therefore, higher concentrations of these radio-isotopes in certain periods in the past indicate times of weaker solar activity and vice-versa. Harnessing this causal correlation, modern science in the 21st century has invented sophisticated techniques to reconstruct the Sun's magnetic cycles, tracing them back over the past 11,000 years [3]. Maunder minimum was not the only time when the Sun went silent; the reconstruction says our host star may have undergone such grand minimum phases for more than 20 times in the past 11 millennia!

While scientists have started unravelling the mystery of solar grand minimum in the last few decades, a lot still needs to be answered. The Sun has a convective envelope surrounding its radiative core where the energy stored in the turbulent plasma currents converts into magnetic energy – a physical mechanism known as the dynamo action. With turbulence comes various stochastic forces in this convection zone, which may occasionally drive this dynamo below a critical threshold, triggering the Sun's magnetic "lullaby".

The emergence of magnetic spots on the Sun's surface becomes very rare during a solar grand minimum, as evidenced in the observation. Does the overall dynamo mechanism fade away completely during such phases? Recent computer simulations spanning across multiple millennia show otherwise [4]. While the overall magnetic field weakens during a grand minimum and also the decennial rhythm breaks, gigantic plasma circulations in the Sun's interior may work ceaselessly, causing a subterranean, however weaker, dynamo action beneath the star's surface. The circulations dredge up magnetic fields from the deep interior and deposit them on the Sun's surface and polar regions. This eventually helps the star regain its magnetic vigour and kick start the decennial rhythm. The simulations also indicate that the hemispheric symmetry in the solar magnetic activity may break during this period.

these gaps, aiming to understand the universe in greater detail.

What if the Sun again goes for another nap? Do we expect another ice age on the Earth? Hard to answer, more so because in the post-industrial revolution era it is not the solar irradiance but the greenhouse gases that predominantly regulate the terrestrial temperature [7]. However, such an event would still offer humanity a rare opportunity to witness a sleeping star!

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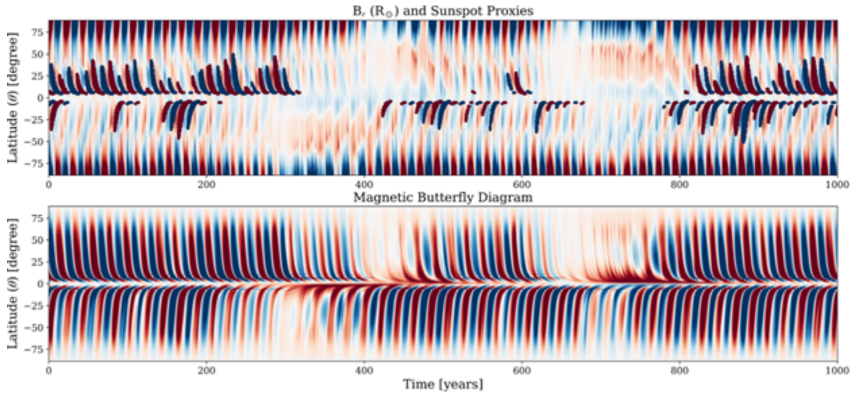

Multi-millennial computer simulation of the solar magnetic activity elucidates occurrences of grand minimum on the sun's surface (top panel) and in the interior (bottom panel). Details can be found in Saha, Chandra and Nandy (2022) MNRAS: Letters. Image: Author

As our reliance on space-based technologies is growing, predicting the Sun's magnetic behaviour across different timescales is becoming more vital. Science has made remarkable progress in deciphering the physics of solar cycles [5,6]. However, we are significantly away from accurate predictions of any impending grand solar minimum. This is partly because their occurrences are not regular at all. Neither can we calculate a priori, in our current capacity, the duration of such an intermittency, hence, nor can we pinpoint its termination. Relentless research continues to bridge

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LEGENDS *and* LIVES

A conversation with one of the most influential figures of quantum computation in India.

Professor Apoorva Patel (left) with Richard Feynman (right) at Caltech, 1984

By
Sheersh Sen,
Amrita Notani,
Ensemble

It rains a lot in Bengaluru. It was raining on the day we met Professor Apoorva D. Patel, in his room. To be honest, it was intimidating enough writing an email to one whose reputation is as grandiose as Apoorva's. His face lit up on seeing us. That gave us unexpected amounts of relief. He had seats for us, all non-uniform in design. Some tradition, woodwork chairs, some casual office seats.

We had heard about the professor emeritus' initial inclination towards lattice QCD and his following shift to quantum computation, where he ended up being an unparalleled giant. We asked him what prompted the change. Apoorva told us of a course he attended while at Caltech, taught by Richard Feynman himself, titled "Potentialities and Limitations of Computing Machines," which sparked his fascination with the subject. "That course, afterwards was converted into a book, which is available as 'Feynman Lectures on Computation,'" he recalls.

Professor Apoorva's superannuation ceremony was recent, in the summer of 2024. What that implied was, that he would no longer take his famed 'Introduction to Quantum Computation' course in the following semester. Either way, we asked him about what made him bring this course to IISc. The professor highlighted the importance of teaching a subject to deepen one's own understanding. He emphasized, "It's a test. How do you know that you understand the subject yourself? And when you are jumping into new things it's a very useful thing to try out teaching it. You learn a lot from that particular exercise." This approach guided his teaching of quantum computation for over 25 years in IISc.

The conversation then shifted to the state of quantum computing education in India. Apoorva acknowledged a gap in the number of educators who can teach the subject of quantum computation from foundational principles. He stressed the importance of building a strong foundation, stating, "They might look at some top level research paper, and then teach content related to it. That is not equivalent to teaching the stuff from the basics."

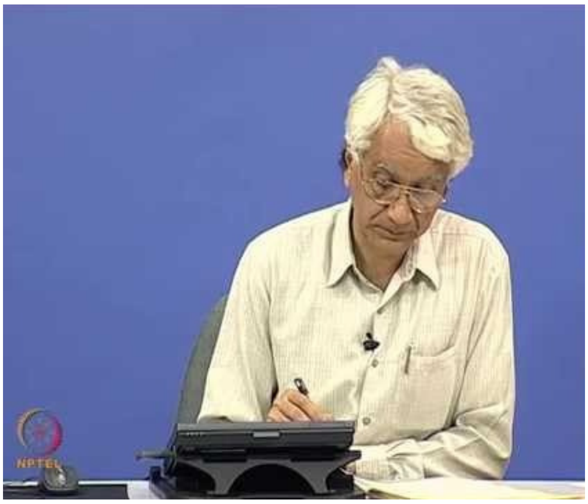
Apoorva sharing his recollections during his superannuation ceremony.

To address this, Apoorva made his video lectures on quantum computation publicly available on YouTube. This was another act displaying his belief in the free dissemination of knowledge.

The discussion turned to the role of theorists in the field. While theoretical foundations are crucial, the current emphasis is on building functional devices. The professor pointed out, "It's an applied subject. It's not about the theoretical exercise." He contrasts quantum computing with mathematics, where the goal is not just deriving theorems but creating something practical.

We came to understand the divide between software (principles) and hardware (implementation) in quantum computing, similar to traditional computing. The professor observes, "The software aspect is way ahead of the hardware part and not only in India but everywhere in the world."

"It's a question of converting science into technology, that's always difficult." He went on about the inevitability of trial-and-error methods in identifying problems suited to quantum computational solutions. This gave way to a discussion on the history of quantum mechanics and how quantum theory wasn't initially created to solve specific problems but to explain phenomena that classical theories couldn't. This historical perspective provides valuable insights for identifying areas where quantum computing can be most effectively applied.



Professor Apoorva during one of his many NPTEL lectures.

Apoorva continued by emphasizing the importance of identifying specific scenarios where quantum theory offers a distinct advantage over classical theories. He highlights that "Planck's constant" plays a crucial role. "So if Planck's constant equals zero there won't be any quantum theory," he states. "You have to look at phenomena where the value of Planck's constant is non-zero " He warns against making blanket statements about quantum superiority, emphasizing that it's "problem-dependent" and not applicable universally.

He then addressed the practical challenges of harnessing quantum phenomena. "We are trying to take advantage of features which are intrinsically at a small scale. The atomic scale, essentially," he explains. "And, you don't have a direct connection with it." He points out the difficulty of maintaining quantum states in the macroscopic world: "maintaining the quantum level of the signal is very difficult. Even if quantum devices work as ideally designed, they will be much more expensive than the classical systems which are already working, like our computers," he stated. He emphasized the need for a significant advantage to offset the increased cost.

The professor suggested that future applications will likely involve "hybrid structures," combining classical and quantum components. This hybrid approach is seen as more realistic and practical than a fully universal quantum system.

Things were about to get interesting. He highlighted the importance of rigorous design and simulation before proceeding to fabrication. "First, a model has to be designed. You have to take care of the software and other controlling parameters and once you're sure that things are reasonably okay, then you move towards the fabrication."

Professor Apoorva then naturally criticized the current state of hardware development in India, particularly the lack of focus on design and simulation. "The Indian industry needs to bring its focus more on design and simulation part of the story and until they do that, we will stay behind as we already are." He warns about the potential consequences of this neglect, including limited technological advancement and increased vulnerability in areas like national security.

> "The Indian industry needs to bring its focus more on design and simulation... until they do that, we will stay behind as we already are.."

The professor delved into the geopolitical implications of advanced technologies. He acknowledged that "wars, direct or indirect" often drive the development of high-level technologies. "Whether you like it or not, it is true." He emphasized that access to cutting-edge technology is often controlled by powerful nations and multinational corporations. This should be a fact all of us have, at some juncture, certainly observed.

"They [stronger nations] are only going to give cloud-based access to other nations for higher-level technology," he explained. "We will get an access to the second-best technology, any practical nation would want to sell older technology they possess. We end up lagging behind them." We're sure to infer that such a model limits true technological advancement and innovation within a country.

Apoorva proceeded to emphasize the importance of indigenous research and development. He cited India's space program and nuclear program as successful examples of independent technological development. Vikram Sarabhai, Homi Bhabha and other visionary scientists pushed and drove these grand, though arduous, initiatives.

"Let the scientists make the roadmap to the future." he asserts. He criticizes the current approach to quantum technology development in India, where bureaucratic hurdles and a lack of scientific leadership are hindering progress.

“Let the scientists make the roadmap to the future.”

Have you ever been disappointed with the lack of funds dedicated to science and research in India? If yes, then Apoorva agrees. He emphasized the need for a dedicated pool of skilled researchers and the importance of long-term investments in building this human capital.

The bureaucratic challenges faced by researchers in India are colossal. "They don't realize that you cannot get any equipment from any company with this kind of constraint," he explained, referring to unrealistic deadlines imposed by funding agencies.

The professor expressed his concerns about the current state of quantum technology development in India. He believes that the lack of a clear vision and effective leadership is hindering progress. He emphasizes the need for a more strategic and long-term approach to developing this critical area.

Here’s another issue in research that goes unnoticed that Professor Apoorva wanted to highlight: the cumbersome process of procuring scientific equipment from abroad.

"You have to first prove that it's not made in India," the professor explained, describing the bureaucratic hurdles researchers face. "You have to advertise, confirming nationwide whether a certain apparatus is available in India, wait months for responses, and then, if no one responds, then and only then can you finally order it.” This absurd process, along with other bureaucratic rules, severely hinders research progress.

“I've been asked: ‘What can you do with whatever you already have?’ We, the researchers, do whatever we can. We have great capabilities, but our hands are tied. Give us freedom." He mentioned numerous times, to reassure us, that he was entirely sure of what he meant to say and of the message he wished to put out there to the world.

“We have great capabilities, but our hands are tied. Give us freedom.”

Pragmatic as he is known to be, Apoorva addressed the challenges of attracting and retaining talent in the field of quantum computing. He stated, "Everybody wishes to know: ‘If I join the field, what lies down the line. What will be my career options?’" He thereafter strongly emphasized and elaborated on the need to provide job security and career stability to attract and retain talented individuals in this field.

Apoorva reiterated aspects of successful indigenous efforts, the Indian space program and nuclear program. Long-term support and stability to researchers are essential, he said. "That takes off a huge amount of load off anybody's head who is interested in working in this field."

Good things we thought. Certainly practical and important. But jobs and stability aren’t the topics plaguing our juvenile undergraduate minds, we thought simultaneously. We pointed this out to Apoorva and he merely gave us a whimsical smile. Proceeding to discuss a seemingly unrelated quantum systems simulator, QSim, developed at IISc. This simulator, freely available online, allows researchers to explore the impact of errors and noise on quantum computations.

"The important point though, is that the code for the simulator was written by undergraduate students," he emphasized, his smile still going steady. Herein lies the potential of undergraduate students to contribute significantly to research under some well directed guidance.

“I think I’ve spoken too long, but this is pretty much all I have. Best of luck with your endeavours.” We got up to depart. The interview went well. It was still raining though.

Check out QSim, the Quantum Computer Simulator Toolket developed at IISc through the following link: https://qctoolkit.in/

MERMIN'S EXPERIMENT

By Arpit Chhabra, Phi@I

Introduction

Every one reading this article must have at least once heard about EPR Experiment or Bell's inequality in a YouTube video(which usually includes long explanations) or in text books (which includes non trivial mathematical results , work of Genius John Bell) but purpose of this article is to simplify bell's inequality in some other experiment which is easier for everyone to understand, it stands amidst with shorter explanation and lesser calculations preserving the Quantum nature of our universe(which is completely credited to David Mermin an aside Richard Feynman called his paper One of the most beautiful papers of physics refereed at the end)

Let's Start with a simple question(maybe not that simple) , what is reality or what is real? Do features exists without presence of observer , are there features of system that are inherent regardless we measure them or not. I mean our common sense says that our presence should not really affects what is real about a system. I will leave to you to think about this question.

Now let me give some context before diving in Mermin's Experiment. You probably have heard quantum mechanics can lead to faster than speed of light travel(I first heard it from michio kaku's video) but where does this idea come from.

Let's say you have A pair of shoes and two boxes , now some third person puts left shoe in one box and right shoe in other and keeps it on table and leave the room , now you and me we don't know which box has which shoe as the boxes are completely symmetrical and weight equally, here let's assume there is no way to know which box has left and right shoe without opening the box , now let's say you take a box randomly selected to Princeton, New Jersey and I'll take my Cambridge, UK , we both can have either left or right shoe, of which we have no idea, and now you open your box and find that it's a left shoe, that means instantaneously(faster than speed of light) , my box will have the right shoe , have we just violated Basic postulate of special relativity without even invoking Quantum mechanics . Wait and Think about it?

Definitely not , regardless of the fact we didn't know information of which shoes was in which box, the information was already there in sort of hidden variable, already decided , just our ignorance about this hidden variable lead to us not knowing, so there was nothing surprising as you would have probably thought. Now the question comes then why are people surprised when same happens in quantum mechanics , let's say you have a pair of electrons that are entangles now with the show you also take an electron with you without making any measurement along the way to Cambridge(in Copenhagen interpretation , without collapsing the wave function) and I'll do the same while travelling to Princeton, Now You at Cavendish laboratory make conduct and experiment to find spin of electron you took in z direction, and result came out to be spin up, as we had entangled pair, instantaneously my electron should have a spin down in z direction regardless of the fact i make a measurement of not. Do you see the similarity between the electrons and shoes but are they really similar, think about it?

As you expected they are not, because unlike for shoes we cannot have a local hidden variable explanation for electrons, gist of issue arises because unlike shoes we can measure spin of electrons in any direction we want so hidden variable have to account for a lot of stuff, which can either turn out to be not possible classically or contradictory. Here's when Mermin's Experiment come in.

First we (Mermin) introduced a device which has some of the following properties:

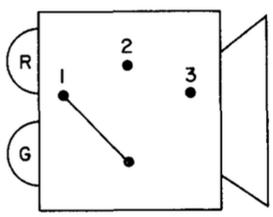


Fig. 1. Detector. Particles enter on the right. The red (R) and green (G) lights are on the left. The switch is set to position 1.

Look at this as old cam recorder , but rather than video recording we are recording some properties of particle entering it could be photon, electron or anything but we can understand this experiment precisely thought experiment with diving deep in to specifications. The experiment includes two of these devices with a source in centre releasing two particles with are related to each other as they are produced simultaneously from the source. Now first rule is we can set each device on any of 1,2,3 setting we like , especially when ever we like but before the particle enters the device. As stated when a particle enters the device flashes either R(Red) or G(Green).

Now as we assumed earlier with shoe box experiment assume that there is no communication between both the devices, in complete isolation relative to each other.

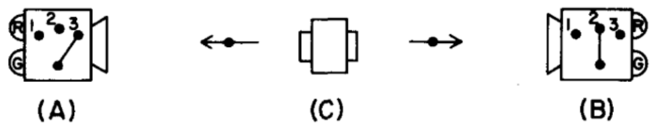


Fig. 2. Complete device. A and B are the two detectors. C is the box from which the two particles emerge.

Now when we run the experiment we get random gibberish of data but if we run the experiment long enough we find patterns which state that.

Case I In those runs in which each switch ends up with the same setting (11, 22 or 33) both detectors always flash the same color: RR and GG occur with equal frequency; RG and GR never occur.

Case II In those runs in which the switches end up with different settings (12, 13, 21, 23, 31 or 32) both detectors flash the same color only a quarter of the time RR and GG occurring with equal frequency); the other three quarters of the time the detectors flash different colors (RG and GR occurring with equal frequency).

Now as a curious person you want to know what's happening, how to know which device will flash which colour beforehand by just knowing the setting of each device. and one of the ways,someone, in this case you and me would like to solve this problem is to introduce some variable(precisely some properties) that a particle being produced might have i mean it should have some properties that's why we are getting some results , keep in mind there is no fundamental difference in between devices and particles that are being released.

Settings		Flash same colours	Flash opposite colours
Device 1	Device 2		
1	1	100%	0%
2	2		
3	3		
1	3	25%	75%
1	2		
2	3		
2	2		
3	3		
3	2		

This table shows final probability of results.

Now getting back to hidden variable, let's denote a particle has 3 independent properties say A, B, C why three? My guess we want each property to correspond to which setting we have on device, Now these three positions can be filled by two properties R and G with any amount of repetitions we want to have. Now I will denote $A_1B_1C_1$ corresponding to particle 1 and $A_2B_2C_2$ corresponding to particle.

From the case I we observed that if we have same settings on both the devices we have same colour , hence $A_1 = A_2, B_1 = B_2, C_1 = C_2$
which is nothing new as we already have particles to be completely identical.

Now observe after assigning R, G at ABC we have 8 ways to assign these properties namely GGG, GGR, RGG, GRG, RGR, RRG, GRR, RRR.
This is completely consistent with case I, as when ever we have same setting we get same colour. But now try to calculate probability when ever we have different setting can we get 3/4 of time opposite and 1/4 same colour , try to do this on your own , I'll give an example , have setting 1,2 -- now see how many cases of these 8 you get the same light and how many of these you get different light (Spoiler Alert!) not the same as Case II. This is the holy grail, we can't assign any way predetermined variables to predicted outcome.

Now any curious reader would have many question but if one of them is why Just these types of setting why not more than three varibles , I would suggest try to find any set of variable if you get consistent answer (You are going to be really popular!!)
Other subtle question being why is outcome already decided what if this can't happen in nature? It definitely can, one way to look at these settings is to think of them as spin operator at 120 degree of each other for people who know what spin is and what an operator is. Many of you are probably feeling is that it, in this article yes this is simplest way to show quantum nature but there is a lot to explore which I leave to you.
A section for people who are a bit aware of what quantum mechanics is and entanglement, another quite easy way to show when quantum mechanics can't be directly explained by this method .

Consider the entangled three-particle state

$$|ABC\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle|\uparrow\rangle|\uparrow\rangle - |\downarrow\rangle|\downarrow\rangle|\downarrow\rangle)$$

Now, we measure $|ABC\rangle$ but here we have a set of operators (Pauli spin matrices) that we will apply which will give us either +1 or -1 eigenvalue after applying them

$$\sigma_x^A \otimes \sigma_x^B \otimes \sigma_y^C|ABC\rangle = \sigma_x^A \otimes \sigma_y^B \otimes \sigma_x^C|ABC\rangle = \sigma_y^A \otimes \sigma_x^B \otimes \sigma_x^C|ABC\rangle = +|ABC\rangle$$

What is shown is after apply these 3 operators we get +1 value , now we go back to before and try to assign hidden variables to them
We would come up with M value corresponding to each operator think of this like settings we had before and we would get

$$M_x^A M_x^B M_y^C = M_x^A M_y^B M_x^C = M_y^A M_x^B M_x^C = +1$$

Here we have each M take ± 1 simple multiplying them together we get

$$(M_x^A M_x^B M_x^C)^2 M_y^A M_y^B M_y^C = +1$$

We can see regardless of anything squared would be positive and get:

$$M_y^A M_y^B M_y^C = +1$$

Seems easy enough but now let's apply

$$\sigma_y^A \otimes \sigma_y^B \otimes \sigma_y^C$$

we get

$$\sigma_y^A \otimes \sigma_y^B \otimes \sigma_y^C|ABC\rangle = -|ABC\rangle$$

another contradiction , so you see it isn't easy and possible in this to have that hidden variable approach.

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Quantum Theory: Concepts and Methods by Asher Peres

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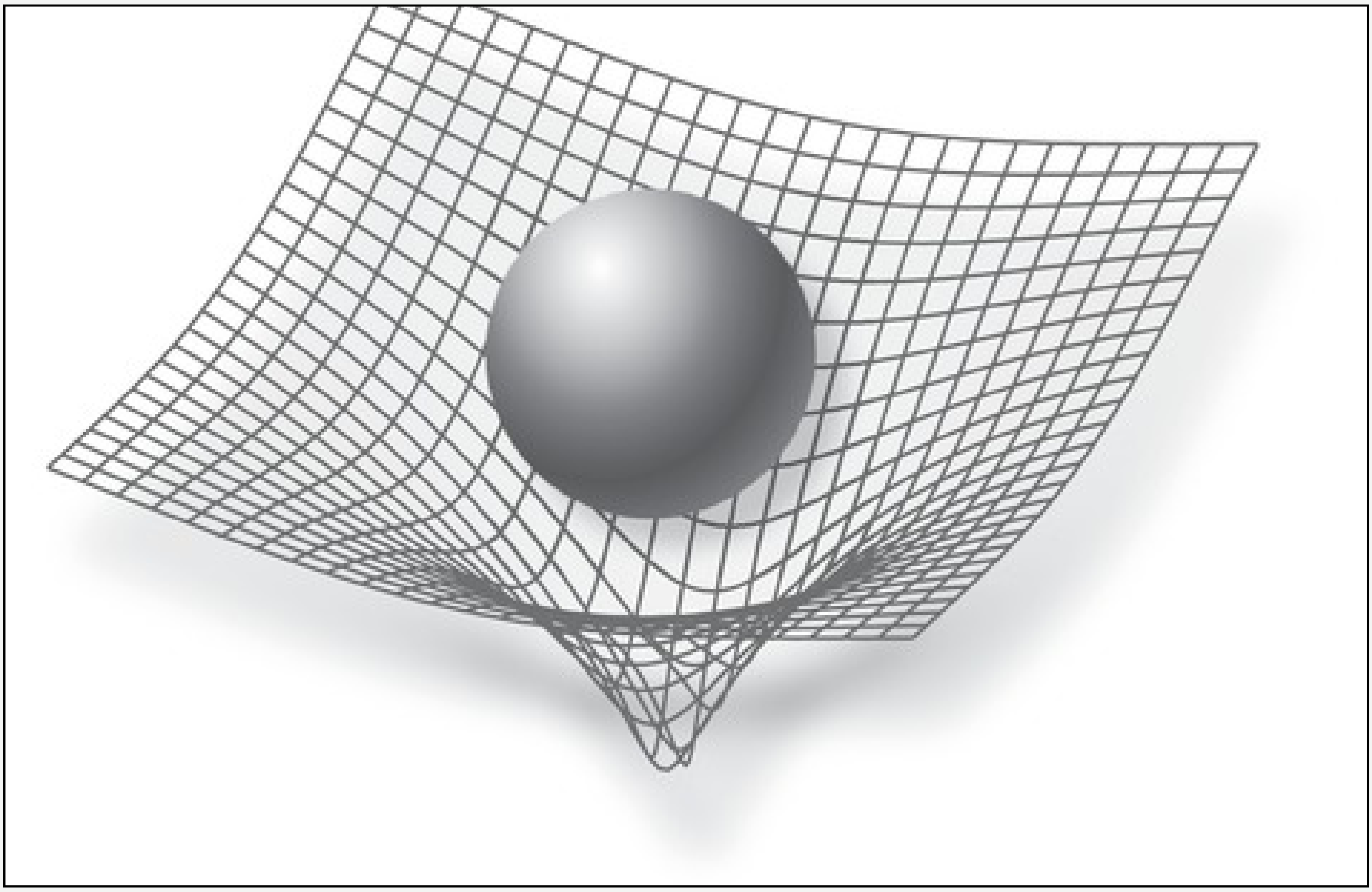
QUANTUM GRAVITY

Bridging Quantum Mechanics and General Relativity

By Debarshi Mukherjee, 137 Inverse



A cartoon depiction of the curvature of spacetime. Source: The Irresistible Attraction of Gravity, Cambridge University Press

In this article, we explored one of the challenges of theoretical physics: bridging quantum mechanics and general relativity by examining quantum gravity's asymptotic safety, emergent spacetime via en tropic gravity, and the discrete nature of spacetime in causal dynam ical triangulations. We also discuss the role of quantum information in shaping spacetime geometry alongside the holographic principles of AdS/CFT. We explore the theories of quantum cosmology, the black hole information paradox, and the concepts of non-locality and causality, which are followed by a discussion on gravitational instan tons and the cosmological constant problem, pushing boundaries for the quest for a unified theory.

Introduction

The search for the unification of quantum mechanics (QM) and general relativity (GR) remains a complex puzzle in modern physics. While GR describes the nature of spacetime and gravity, QM gives an idea in the subatomic realm, making these two pillars of theoreti cal physics fundamentally incompatible. This article approaches the problem via discussions on mathematical framework and concepts, focusing on some advanced theories. By exploring these topics and current research, we aim to get insights into the possible quantum structure of spacetime geometry

The Incompatibility Problem: Where QM and GR Clash:

In QM, a quantum system's state is described by a wave function psi, which follows the Schrodinger equation, $\psi(x,t)$, which follows the Schrodinger equation:

$$i\hbar\frac{\partial\psi(x,t)}{\partial t} = \hat{H}\psi(x,t)$$

where $\hat{H}$ represents the total energy of the system (Hamiltonian Operator) . QM is probabilistic (Born Rule) and as fundamental aspects of QM, Quantum superposition, entanglement and the uncertainty principle challenge the classical intuition.

Instead of a force, GR describes gravity as spacetime curvature caused by mass and energy, explained by Einstein field equation:

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

where, $R_{\mu\nu}$ is the Ricci curvature tensor, $g_{\mu\nu}$ is the metric tensor, R is the Ricci scalar, Λ is the cosmological constant, G is the gravitational constant, c is the speed of light, and $T_{\mu\nu}$ is the stress-energy tensor. GR conflicts the probabilistic nature of QM. The central problem in reconciling GR with QM is the nature of spacetime. GR describes spacetime as continuous and smooth manifold but in QM, space and time are subject to quantum fluctuations. Non-renormalizable infinities are encountered whenever we tried to quantize gravity. For example, GR predicts a singularity in black holes where spacetime curvature becomes infinite. Quantum effects are expected to dominate, but without a quantum theory of gravity, these are just predictions. Also, in Planck scale, we understand the incompatibility clearly since we need to consider both quantum and gravitational effects. Here, except string theory and loop quantum gravity, we will see other approaches of unification.

In the quest of an explanation of gravity as per principles of QM, the following are some proposals we could discuss, (apart from string theory and loop quantum gravity, of course!)

Asymptotic Safety in Quantum Gravity

Asymptotic safety is a proposal that, the renormalization group (systematic investigation of the changes of a physical system as viewed at different scales.) flow of quantum gravity reaches a non-trivial fixed point at high energies, making it

well-defined at all energy scales. It contradicts the traditional view that quantum gravity must be non-renormalizable.
The effective action $\Gamma_k[g]$ depends on k, a scale parameter, and as $k \to \infty$ the theory flows towards an ultraviolet fixed point in a finite dimension. This theory provides a finite, predictive QTG without new entities like strings/loops, implicating gravity a QFT like standard model.

Entropic Gravity

This concept yields that gravity is not a fundamental force, it is a statistical behavior at microscopic level that emerges due to the tendency of systems to increase entropy. The force, F, follows the thermodynamic relation:

$$F = T\frac{\Delta S}{\Delta x}$$

This approach challenges our fundamental understanding of spacetime.

Causal Dynamical Triangulations (CDT)

CDT models QTG using a discrete spacetime lattice, a piecewise linear manifold, ensuring causality by distinguishing between spacelike and timelike seperations. It's framework as path integral is:

$$Z = \sum_{\mathcal{T}} \frac{1}{C(\mathcal{T})} e^{iS_{EH}(\mathcal{T})}$$

where $\mathcal{T}$ represents different triangulations, $C(\mathcal{T})$ is the symmetry factor, and S_{EH} is the discretized Einstein-Hilbert action.
CDT has shown promising results to preserve classical structure of spacetime, unlike other approaches.

Quantum Information Theory (QIT) and Gravity

In QIT, has revolutionary implications for QTG by providing connection between information and spacetime structure. For example, the Ryu-Takayanagi formula relates entanglement entropy (S_A) of a QFT to the area of a minimal surface (gAγ_Aı the dual Ads in a higher-dimensional spacetime, suggesting the geometry is connected to quantum information:

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

G_N is Newton's constant.

AdS/CFT Correspondence and Extensions

Here, different physical theories describe the same phenomena as a broader set of dualities, making QTG a cosmologically relevant context. Mathematically:

$$Z_{QFT}[\phi_0] = Z_{gravity}[\phi_0]$$

where Z_{QFT} is the partition function of the boundary CFT, and $Z_{gravity}$ is the partition function of the bulk gravitational theory.

Quantum Cosmology and the Early Universe

The Hartle-Hawking no-boundary proposal describes the universe's origin as a quantum fluctuation described by Euclidean-spacetime without a boundary, avoiding the singularity in GR. During inflation, the wavefunction wavefunction $\Psi[h_{ij}, \phi]$ of the universe is given by (Wheeler-Dewitt equation):

$$\hat{H}\Psi[h_{ij}, \phi] = \left(-\frac{16\pi G}{c^4} G_{ijkl} \frac{\delta^2}{\delta h_{ij} \delta h_{kl}} + \frac{c^4}{16\pi G}\sqrt{h}\left(R^{(3)} - 2\Lambda\right)\right)\Psi[h_{ij}, \phi] = 0$$

where h_{ij} is the 3-metric, G_{ijkl} is the DeWitt supermetric, and L is the cosmological constant.

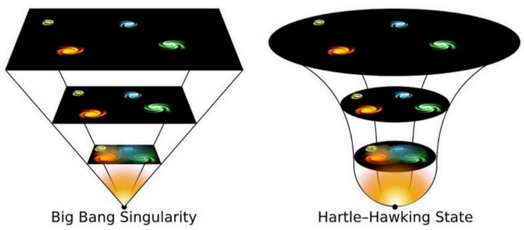


Figure 1: The universe according to Hawking [1]

The Black Hole Information Paradox

This paradox arises regarding fate of information in black hole evaporation, conflicting QM and GR. Black holes may radiate energy through Hawking radiation, leading to loss of information, which violates unitarity of QM. Holographic principle suggest that information may be encoded on the event horizon of the black hole. Figure 2 contains a brief summary of the problem.

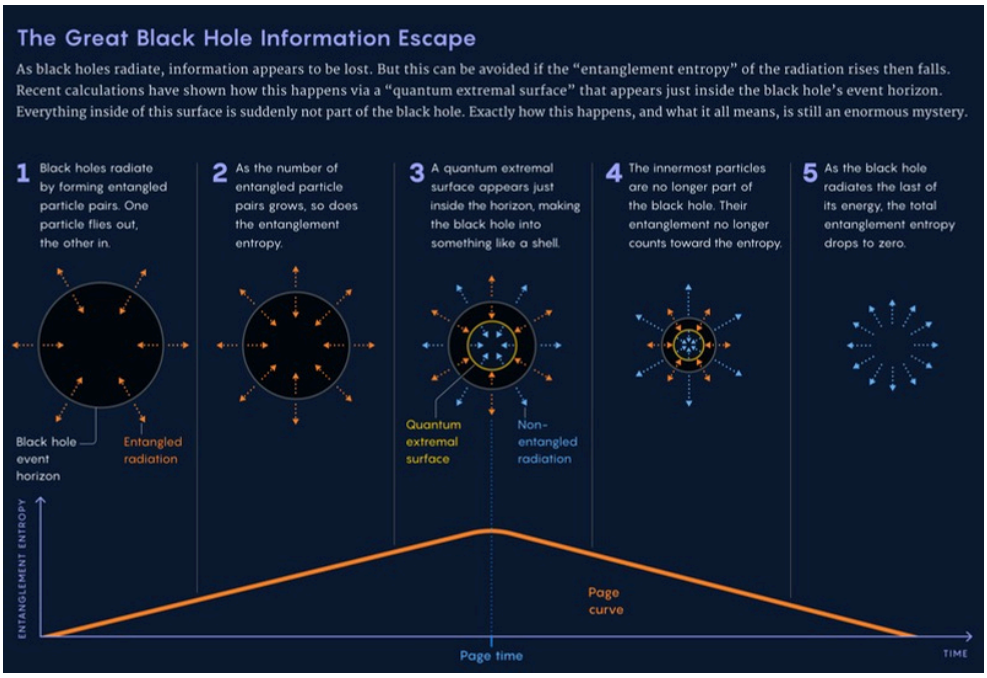


Figure 2: The black hole information paradox [2]

Non-Locality in Quantum Gravity

QTG might challenge classical notions of locality. In general, the causal set approach postulates that spacetime is discrete and consists of events with a partial order, arising non-locality. The 'ER=EPR' conjecture suggests a connection between quantum entanglement (EPR) and wormholes (Einstein-Rosen bridges) to give a description of spacetime at Planck scale.

Quantum Tunneling and Gravitational Instantons

Gravitational instantons are Euclidean solutions to Einstein's equations contribute to quantum tunneling processes in gravity describing the creation of baby universe, given by:

$$S_E = -\frac{1}{16\pi G}\int d^4x\sqrt{g}\,(R-2\Lambda)$$

Here the symbols are as defined earlier.

Quantum Vacuum and the Cosmological Constant Problem

QFT predicts a vacuum energy density ρ_{vac} which is vastly larger than the observed value associated with dark energy (even at Planck scale), leading to cosmological constant problem. The prediction is:

$$\rho_{vac} = \frac{\hbar}{2}\int \frac{d^3k}{(2\pi)^3}\sqrt{k^2+m^2}$$

Supersymmetry/quantum vacuum contributions may resolve this problem.

Future Direction

The Chinese-Austrian quantum satellite Micius is developed to examine the behavior of entangled photons in different gravitational potentials, leaving open the possibility of discovering a unified framework connecting QM and GR experimentally. The team has performed quantum key distribution between Micius and ground stations. Such experiments demonstrate the secure satellite-to-ground exchange of cryptographic keys during the passage of the satellite Micius over a ground station.

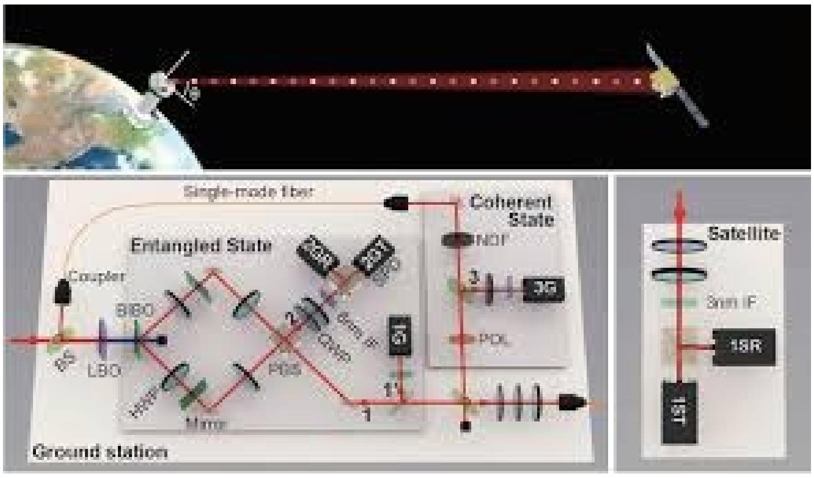


Figure 3: Experimental idea behind Micius [3]

Conclusion

The unification of QM and GR is an ongoing journey. Theoretical developments like Ads/CFT, CDT and groundbreaking experimental work represent a promising step forward. Refining our understanding of cosmos promises the dream of unified theory may come closer to reality, bridging the divide between the quantum and the cosmic.

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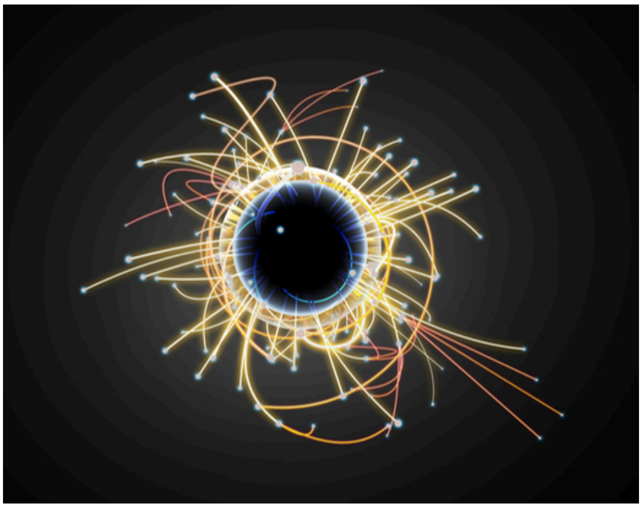
A PHYSICIST'S MIND

An interview with Prof. Ujjal Kumar Dey, Department of Physical Sciences, IISER Berhampur

By Ayaskanta Panda, Prachiti Sharma, Anika Majumder, Sudeep Das, Suvo Sengupta
137 Inverse

How has the discovery of the Higgs boson, called the god particle, changed the theoretical approach in particle physics? How has it improved our way of understanding the fundamental nature of the universe?

Physicist Leon M. Lederman (along with science writer Dick Teresi) wrote a book on Higgs boson. He was a famous experimental scientist, received Nobel prize for his research on neutrinos. He wanted to put the title of the book as The God-damn Particle (because such an important particle was so elusive in experiments). And the publishers were not at all happy about the title. So they changed it to The God Particle. And that's how the name stuck to it. The Higgs boson is the particle theorised to give mass to all the particles. What happens is that in particle physics, we know that there are fundamental particles and fundamental interactions, right? I think you may have heard about fundamental particles like quarks, leptons, and electrons. So, when the theory of standard particles was made, it had a pleasing symmetry. But if you have symmetry, then the mass of those particles cannot be explained. So, to explain how the particles got their masses, they brought in the idea of spontaneous symmetry breaking by means of Higgs mechanism. And actually, it is not just Higgs alone. Many others (Kibble, Guralnik, Hagen, Englert, Brout) contributed to that idea. So that was the 60s. But after that, it took almost 50 years to discover it at the LHC. When found, it confirmed the fundamental theory for the primary particles, and interactions. This enhanced our understanding of the fundamental interactions. However, even after its discovery, research is still going on to measure various properties of that particle.



We see that researchers use different models to prove findings in an experiment. Can you shed some light on the thought behind the formation of the model?

There are different kinds of models people come up with to explain various things. The better your theory is, the more things it can explain. However, it is challenging to develop a theory or model explaining everything. That is why we try to develop a theory that can explain some of the observations. So, we can see how much we can embed within one model. However, the problem is that theorizing a model and testing it in a experiment are two completely different endeavours. We must be careful how we can test a theory. As long as there's no experimental verification, no matter how beautiful the theory is, it is just a theory. Once we have some experimental observation, you can zero in on a definite model or theory. That is why there are so many models and so many experiments going on. The job of all these experiments is to cut down all the redundant theories. With more experiments and data, we can concretize our theories and eliminate the wrong ones.

What are some recent discoveries in neutrino physics that you find exciting and why?

None of them are very recent. One of the latest (1998) exciting thing that was observed was something called neutrino oscillation. The standard model was built so that neutrinos would not have any mass. However, this experiment showed that neutrinos have tiny mass. So, this is one of the most significant recent discoveries in the field of neutrinos. Detecting the neutrino itself was a big challenge because it is electrically neutral and was considered massless. But we are not sure of so many other properties, such as what type of particles these neutrinos are or their exact mass etc. From the current experiments we can at most, know about the mass-squared differences between different neutrino states. The precise mass of the neutrinos still needs to be measured. Current experiments are trying to determine that. They're also trying to find what kind of particle this neutrino is – whether it is its antiparticle.

Can you explain how neutrino particles are detected in neutrino detectors?

First time it was done during mid-fifties, by Cowan and Reines at Los Alamos National Laboratory. They used the idea of inverse beta decay ($\bar{\nu}_e + p \rightarrow e^+ + n$). The enormous flux of antineutrinos from a nuclear reactor at the Savannah River Plant in South Carolina is used on the “target” consisting of cadmium chloride dissolved in water. This was surrounded by large detectors 4 filled with a liquid scintillators. The underlying process produces characteristic flashes of light in the scintillator, like when the positron annihilates with an electron (within the medium) to create two gamma rays (high-energy photons). The neutron bounces around for a few microseconds and is then captured by an atomic nucleus, producing another gamma ray as the nucleus releases excess energy. So you can say the neutrinos originated from nuclear reactors (which are used for power generation) were detected for the first time in history.

> “The main driving force behind all these things should be your interest.”

What was your motivation to become a theoretical physicist? What were the challenges you faced as a theoretical physicist?

Okay, so the first thing was that I like mathematics a lot. Clearly, that is the most cliched answer to this question. But more than that, it is the idea that just some mathematical equations can describe nature appealed to me a lot when I was a kid. And that was the primary motivation for me. About the difficulty and challenges, if you want to do anything, be it theoretical or experimental, you must put in a lot of hard work. If you are passionate about it, the hard work will not feel that much. So I would tell all the students that you should follow whichever topic you find most interesting and not go by the glamour.

Since you are very experienced in the field of beyond standard model physics, Can you briefly explain some of the fundamental flaws or anomalies of the standard model due to which we require the beyond standard model theory?

When I’m talking about the standard model, you should know that it is the theory of the fundamental particles and their interactions. The particles are – six types of leptons (electron, muon, tauon, and three types of neutrinos), six types of quarks; these are all fermionic particles. Then there are other types of particles which are bosonic in nature and behave as mediator of fundamental forces, for example, photon for electromagnetic interaction, $W^{\pm}$ and Z boson for weak interaction, gluon for strong interaction. Gravitational interaction is kept out of it since we do not have any consistent quantum theory of gravitation. And lastly there is Higgs boson. This standard model explains more or less everything subatomic. But, there are certain observations for which you need things beyond the ambit of the standard model. As I said before, first, you can not explain the neutrino mass within the standard model. You can explain all the other particle’s mass using the Higgs mechanism, but not for neutrinos because, experimentally, no one has ever seen the right-handed variant of neutrinos. So, we need to work beyond that. Then, this dark matter, again, from some astrophysical observations, we know that there exists some form of matter that none of these particles can explain. So, that is again something that tells us we need to go beyond.Then, we talk about all this normal matter, but where has all the antimatter gone?We assume that both matter and anti-matter were formed equally at the origin of the universe, the big bang. These three direct observations tell us that we need to go beyond. But then there are also certain aesthetic things – something to do with the Higgs boson mass and many other things. However, some of those things are prejudices that make us want the theory to be beautiful. Nature may not be like that. But these three observations are crucial. These are not aesthetic issues but hard facts.So you have to explain them, and you have to go beyond the standard model for that.

Based on your recent paper, Gravitational Wave Probe of Primordial Black Hole Origin, can you explain how gravitational waves play an essential role in finding the origin of primordial black holes?

So, what are primordial black holes? Maybe you have heard about black holes, but the primordial black hole is a different beast. The black holes you know of involve a star; the entire fission process continues, and eventually the hydrogen (fuel) is finished. If the star's mass is usually higher than Chandrasekhar limit, it will go into a black hole state. That is what you know. That is the usual astrophysical black hole. But these primordial black holes are different. It is primordial because these are the black holes that, by some theories, were formed way back in time before even any star was formed.Just after the Big Bang as the universe was still getting bigger, it was an extreme place full of subatomic particles and lots of energy. Inside this extreme place, there were pockets where matter was very denser than its surrounding. In such places, gravity caused some kind of collapse and that might have created primordial black holes. The astrophysical black holes cannot explain the origin of the supermassive black holes which are present in the centre of galaxies. So people think those primordial black holes were a source of the supermassive black holes we see nowadays.This is more or less all about primordial black holes. Now,suppose we have them, but how do we detect them? According to Stephen Hawking's theory, black holes can evaporate. "Evaporate" in the sense that they can radiate some particles. Any kind of black hole can evaporate and radiate different particles. Now, these primordial black holes can also evaporate. So, they can emit some photons or radiate some electrons. Now you have observations, of gamma rays etc., from the galaxies and even the galaxy's centre and from many other directions around the sky. According to the theory, there are primordial black holes, which are also evaporating. You can now calculate how much, say, gamma ray you are expecting and from your telescopes you know how much you are getting. By comparing these two you can say that the density of the primordial black holes will not be that high, or the mass of the primordial black holes will not be this much etc. That is just an indirect way of getting information about the primordial echoes. Now, the work that you are referring to, in that we were trying to see certain features in gravitational waves to test some of the mechanisms of primordial black hole's birth.

image credit :www.astronomy.com

What future dark matter experiments do you consider attractive for new research and why?

This question requires some background– there are specific astrophysical observations from which we can be sure that there exists some form of matter unlike any known matter. We know that it interacts with gravitation because everything that has something to do with the mass will have a gravitational interaction. But other than that, we need more information about it. There are so many theories for dark matter as well- the particle is just one kind of theory. You can say that maybe supermassive black holes are the dark matter. There are specific pros and cons for all those theories. Dark matter experiments try to detect it directly by assuming dark matter is everywhere with some density. We can build some detectors and try to detect those. So, many detectors have already taken data (experiments like CDMS, CRESST etc.), and some have already been proposed (experiments like XENONnT, LUX-ZEPLIN etc.). The dark matter experiments we are considering are mainly like this direct way of detecting dark matter. There are always indirect ways, such as the galactic rotation curve, gamma rays etc. If the dark matter is of particle nature– what are their masses and things like that can be directly estimated from direct detection experiments.

Sir, how do you manage both teaching and research? Kindly give a perspective.

This is a very misleading concept that these two things are to be managed differently. They are so much connected, and both complement each other. Most of the time, when students ask questions I can get a new way of looking at things. Maybe I have not thought about a thing in a definite way. So, if you ask even stupid or even most stupid questions, sometimes that can also be enlightening for me. That is why you must ask questions all the time. And teaching, as I said, is rewarding as long as things are interactive , and if it is so nothing can be better. I learned (and learning) so many things in the process. Let's say I'm teaching a definite course, when I read it during my college days or so, I read it in one way and when I'm preparing for a lecture or taking a class, and students ask questions, that gives me a new perspective. And it is not just about the courses that I'm teaching. For example, even in research, when I'm discussing with my PhD students and the postdocs. Most of the time, if the students are enough hard-working and read enough research articles, they can come up with brilliant new ideas, questions, and problems. Yeah, teaching and research are significantly connected and should never be seen as two different things to be managed separately.

THAT'S ALL FOLKS!

January, 2025

Issue 01

THE CANONICAL

THE INTER IISER-IISC PHYSICS MAGAZINE