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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*

Welcome to the second issue of The Canonical!

The Canonical began as an effort to bring together diverse ways of thinking about physics on a single, collaborative platform. Its first edition showed that such a project could be both feasible and meaningful, bringing together contributions that ranged from technical discussions to broader reflections on the practice of physics. Initiated in 2024, the magazine was conceived with 2025, the International Year of Quantum Science and Technology, in mind.

Collaborative projects are rarely simple, and this was no exception. Conceptualizing, writing, and designing a physics magazine for a broad audience, without any assurance of direct engagement or feedback, posed significant challenges. Yet the value of attempting such an endeavor was clear, and we chose to move forward.

With this second edition, we build on the foundation laid earlier, refining the magazine's scope and direction through experience. This issue spans a wide range of topics, from sonoluminescence to the cosmic microwave background, across multiple subfields and physical scales. The articles present physics not as a collection of isolated subjects, but as a connected and evolving body of ideas shaped by both theory and experiment. Alongside technical pieces, the issue features informal articles and insightful interviews with scientists from our institutes. We hope you enjoy reading it—and that you come away having learned at least one new thing.

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The CMB and Its Polarization

Sarthak Arora, Simar Narula

In 1964, while working at Bell Laboratories A. Penzias and R. Wilson faced an unexpected issue. Their horn antenna consistently recorded an excess noise temperature of about 3 K. They could not eliminate this signal, nor could they find any known source for it. More confusingly, this excess noise was isotropic; regardless of where they pointed the antenna, the signal remained the same. This unexplained temperature excess became one of the most significant discoveries in modern cosmology: the Cosmic Microwave Background (CMB). It is the oldest light in the Universe, released when radiation could finally travel freely without frequent interactions with matter, around 380,000 years after the Big Bang. In this article, we will explore the origin of the CMB and its key observed properties, with a focus on polarization, which is an active area of research in modern cosmology. To understand these ideas, we first need to start with a discussion on basic cosmology.

The Standard Cosmological Paradigm

As the opening lines of the famous sitcom *The Big Bang Theory* put it:

***Our whole Universe was in a hot dense state,
Then nearly fourteen billion years ago expansion started. . .***

Indeed, the modern description of our Universe begins with the Big Bang model, which postulates that space itself has been expanding from an initially hot and dense state. This expansion is encoded in the scale factor 'a', which describes how physical distances grow with cosmic time. The dynamics of a(t) are governed by the Friedmann equations, derived from Einstein's equations of General Relativity under the assumption of large-scale homogeneity and isotropy. While we will not dwell on their details here, but their key implication is clear: the Universe is expanding, and its contents cool as it does so.

Inflation and the Early Universe

According to the standard cosmological picture, the early Universe underwent a phase of extremely rapid expansion known as cosmic inflation, occurring roughly 10^{-36} to 10^{-32} seconds after the Big Bang. During this brief interval the scale factor increased e^{60} to e^{70} times. As a result, regions that were initially microscopically small were stretched to astronomical sizes. While the precise physical origin of inflation is still not fully understood, this phase plays a central role in shaping the large-scale structure of the Universe and will become important later in our discussion.

Following inflation, the standard model particles formed and the Universe became hot and dense. At these early times, the temperature was so high that atoms could not exist. All baryonic matter was in the form of a fully ionized plasma consisting of protons, electrons, and other light nuclei, immersed in an enormous bath of photons. The photons vastly outnumbered the baryons with a ratio of a billion to one.

As the matter in the early Universe was completely ionized, there existed an abundance of free electrons. These free electrons scattered photons via Thomson scattering, causing photon–electron interactions to occur extremely frequently. As a result, radiation could not propagate freely through space. Instead, photons and baryonic matter formed a tightly coupled plasma, continuously exchanging energy. This caused matter and radiation to be in thermal equilibrium throughout this early epoch.

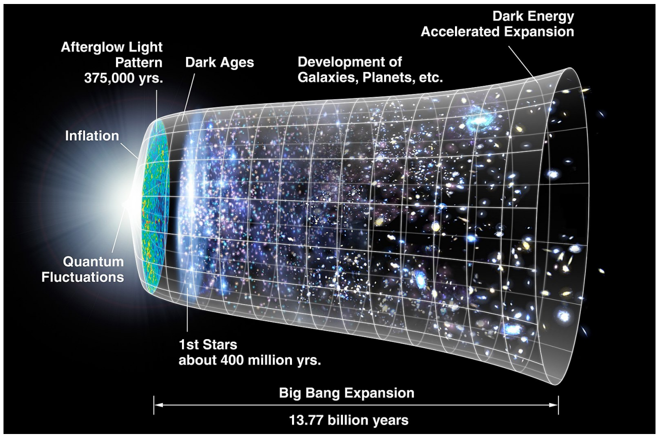


Figure 1: Timeline of the expansion of the universe (Image credits:Wikipedia)

Recombination and the Release of CMB

As the Universe expanded, it continued to cool. Eventually, at a temperature of about 3000 K, corresponding to a cosmic age of approximately 380,000 years, electrons and protons were able to combine to form neutral hydrogen atoms. This transition period is known as the Recombination. As recombination progressed and free electrons rapidly disappeared, the Thomson scattering rate dropped dramatically. Photons were no longer frequently scattered, and their mean free path increased rapidly. Radiation effectively decoupled from matter and began to travel freely through space. It is these photons which now make up the Cosmic Microwave Background.

The region in spacetime from which these photons originate is often referred to as the surface of last scattering, though it is in fact a finite thickness in time rather than a sharp surface. Because these photons last scattered when the plasma was in near-perfect thermal equilibrium, the CMB possesses an almost ideal blackbody spectrum.

Since their release, the Universe has expanded by a factor of about $\sim$1100, redshifting the CMB photons from visible/infrared energies down to the microwave regime.

Observational Confirmations

Satellite missions such as COBE, WMAP, and Planck have measured the CMB spectrum extraordinary precision. The observed spectrum is an almost perfect blackbody with a present-day temperature of $\mathbf{T_0 = 2.725K}$. This is precisely the excess temperature detected by

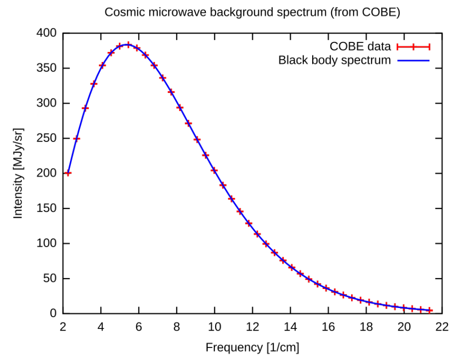


Figure 2: The COBE Spectral data showing the nearly perfect blackbody fit (Image credits: Wikipedia)

Penzias and Wilson in 1964. It should now be evident why this radiation is observed from all directions: it was released everywhere throughout the Universe at the 'last scattering', and we are immersed within it.

Temperature Anisotropies and the Angular Power Spectrum

So far, we have described the Cosmic Microwave Background as a nearly homogeneous bath of radiation with a blackbody spectrum at a temperature of 2.7 K. However, precise observations reveal that the temperature of the CMB is not exactly the same in all directions. Instead, it exhibits small spatial variations across the sky, known as *temperature anisotropies*. The relative magnitude of these fluctuations is

$$\frac{\delta T}{T} \sim 10^{-5}, \tag{1}$$

indicating that the deviations from homogeneity are extremely small, yet non-zero.

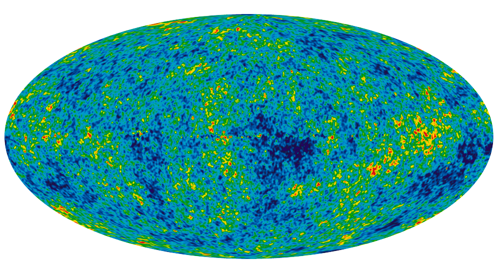


Figure 3: Full-sky map of CMB temperature anisotropies with the mean temperature subtracted. The colour scale shows temperature fluctuations δT at the level of tens of microkelvin.(Image credits: Wikipedia)

These inhomogeneities are believed to have originated during cosmic inflation. During this period, quantum fluctuations of the inflation field were stretched to macroscopic scales. These fluctuations later manifested as small density and velocity perturbations in the photon-baryon plasma. At recombination, when photons decoupled from matter, these perturbations were imprinted onto the radiation field. We now observe these pertubations as temperature anisotropy in the CMB.

Angular Structure of the Anisotropies

The temperature anisotropies are distributed across a wide range of angular scales on the sky. When we examine the CMB at very large angular scales, we observe broad, sweeping temperature variations. As we probe progressively smaller patches of the sky, finer structures begin to emerge. This scale-dependent behavior tells us that we need a framework that can systematically capture the distribution of fluctuations across all angular scales.

To describe this structure quantitatively, it is natural to decompose the temperature field into spherical harmonics,

$$\frac{\delta T(\hat{n})}{T} = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\hat{n}), \tag{2}$$

where $\hat{n}$ denotes a direction on the sky. This is analogous to decomposing a periodic function into Fourier components. The coefficients $a_{\ell m}$ quantify the contribution of each harmonic mode to the observed temperature pattern. Each multipole moment ℓ corresponds approximately to angular variations on a scale

$$\theta \sim \frac{\pi}{\ell}. \tag{3}$$

Thus, low values of ℓ describe temperature fluctuations extending over large angular regions, while higher ℓ probe progressively smaller angular scales.

The Angular Power Spectrum

Rather than cataloging every hot and cold spot on the CMB sky, we characterize their distribution statistically through the angular power spectrum. Think of this as measuring how much temperature variation exists at each angular scale, from the largest structures spanning the entire sky down to the smallest details we can resolve.

To put this in mathematical terms, we define the angular power spectrum as

$$C_\ell = \langle |a_{\ell m}|^2 \rangle, \tag{4}$$

where the angular brackets denote an average over all values of m for a given multipole ℓ.

The quantity C_ℓ measures how much power (or variance) the temperature fluctuations carry at angular scale ℓ. This gives us a complete statistical description of the CMB anisotropies without needing to track individual hot and cold spots.

When we plot the observed power spectrum, something remarkable emerges. Instead of a smooth curve, we see a distinctive pattern of peaks and valleys. This is not measurement error or instrumental noise. These oscillations are real physical features that encode fundamental information about conditions in the early Universe.

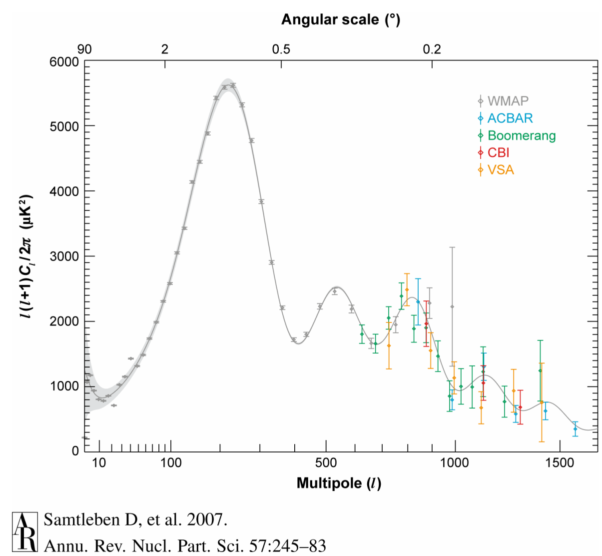


Figure 4: Observed angular power spectrum of CMB temperature anisotropies, plotted as $\ell(\ell+1)C_\ell/2\pi$ versus the multipole moment ℓ. The factor $\ell(\ell+1)/2\pi$ approximately flattens the spectrum at large ℓ, making the oscillatory structure more apparent. (Image credits [8])

Acoustic Oscillations

What causes this oscillatory pattern? The answer lies in sound waves (longitudinal pressure waves) that propagated through the primordial plasma before recombination. Recall that before recombination, photons and baryons were tightly coupled through Thomson scattering, forming a single fluid. Any small density perturbation in this fluid led to two competing interactions. Gravity acted to pull more matter into the overdense region, trying to enhance the perturbation. But the immense radiation pressure from the trapped photons pushed back, resisting gravitational collapse.

This competition did not lead to equilibrium. Instead, it set the plasma into oscillation. Overdense regions compressed under gravity, building up pressure until the photon force became strong enough to reverse the collapse. The plasma then expanded, overshooting equilibrium, which allowed gravity to pull it back again. These oscillations were sound waves rippling through the photon-baryon fluid.

Different perturbation modes oscillated at different frequencies, determined by their wavelength. Consider a perturbation of a particular physical size. From the moment it was created (say, during inflation) until recombination, it had a fixed amount of time to oscillate. Depending on its wavelength, it might complete half an oscillation, a full oscillation, one and a half oscillations, and so on.

At recombination, photons decoupled from matter. Thus the oscillations in baryon-photon plasma were instantly frozen into the CMB radiation. Perturbations that happened to be at an extremum of their oscillation cycle at that moment left the strongest imprint. Modes at maximum compression created the hottest spots, while modes at maximum rarefaction created the coldest spots. These extrema show up as peaks in the angular power spectrum.

The first acoustic peak at $\ell \approx 220$ corresponds to perturbations that completed exactly half an oscillation by recombination, reaching maximum compression just as the photons decoupled. The second peak comes from modes that completed a full oscillation and were maximally compressed again. The third peak corresponds to one and a half oscillations, and so on. The valleys between peaks represent modes caught at intermediate phases, contributing less power.

Polarization

The temperature anisotropies in the CMB had a severe consequence that made the CMB photons linearly polarized. A detailed study of the sources of these polarization and the obtained spectrum can open doors to new physics and might even close for a few.

Thomson scattering, the elastic scattering of photons with electrons (here), plays a key role in the polarization of the CMB photons, and the cross section depends on polarization as

$$\frac{d\sigma_T}{d\Omega} \propto |\epsilon \cdot \epsilon'|^2$$

where ϵ (ϵ') are the incident (scattered) polarization directions. The incident light sets up oscillations of the target electron in the direction of the electric field vector $\mathbf{E}$, i.e. the polarization. The scattered radiation intensity thus peaks in the direction normal to, with polarization parallel to, the incident polarization. By the very nature of the production of this polarization, its linear nature can be realized.

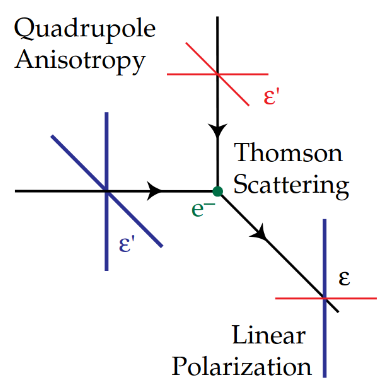


Figure 5: Production of polarization via Thomson Scattering (Image credits: [6])

It can also be observed from Figure 5 that an isotropic radiation field would have changed the mechanism to give an unpolarized light. One radiation field that can produce this polarization is a *Quadrupolar radiation field* (the peaks of “hot" and “cold" spots have an angular variation of $\pi/2$), and due to the orthogonality of spherical harmonics, these are the only ones responsible. The polarization of the photons have a major contribution from the scattering that occurred near the Surface of Last Scattering, because that was the time when the mean free path of photon increased and the cancellation of the net polarization effect due to repetitive scattering decreased, and one of the reasons why the study of the CMB Polarization is important is because it contains important information of this particular instant of time. When one tries to understand the polarization state of EM radiation, he realizes that not all polarization states are the same. Stokes Parameters is what determines the exact polarization state of an EM radiation. We will just provide a few equations related to the parameters and won't go into the details of this.

Stokes Parameters is a measure of the intensity and polarization of the light. Talking about the polarization specifically, we have three parameters, Q, U, V, where Q represents the linear polarization state (conventionally along x or y axis), U along a 45° tilted axis wrt x-y axis (a-b axis), and V is a measure of circular polarization but in this study, we set it to 0 due to reasons mentioned earlier. (Note: People reading the Stokes Parameter for the first time might want to read about why we need U when we already have Q, also see Figure 6)

$$Q = |E_x|^2 - |E_y|^2$$
$$U = |E_a|^2 - |E_b|^2$$

The net Linear Polarization state can be given by,

$$P = Q + iU$$

One problem arises when axis is rotated and Q and U transforms in such a way that it makes calculations difficult. A need for new parameters was, thus, realized that transforms like scalar. Speaking of rotations, one can perform this transformation and see that the net polarization transforms like a spin-2 field. We, therefore, use the spin weighted spherical harmonics to decompose the parameters (spin weighted because the usual spherical harmonics turned out to be insufficient for the description of polarization). The nomenclature of E and B refers to the gradient-like and curl-like nature of the electric (**E**) and magnetic (**B**) fields. E-modes have a gradient and zero curl, while B-modes have zero gradient and non-zero curl. Alternatively, one can see the E and B modes are the parity eigen-states of polarization.

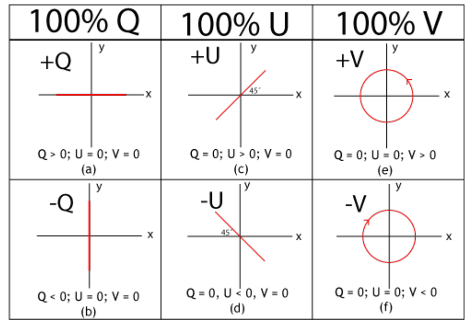


Figure 6: Visualization of the polarization part of Stokes parameters (Image credits: https://en.wikipedia.org/wiki/Stokes_parameters)

E modes have even parity (scalar) while B modes have odd parity (pseudo-scalar) (see Figure 7).

$$(Q \pm iU)(\hat{n}) = \sum_l \sum_m (E_{lm} \pm iB_{lm})_{\pm 2} Y_{lm}(\hat{n})$$

The Quadrupolar variation corresponds to $l = 2$ in spherical harmonics and will have allowed multipole values of $m = 0, 1, 2$. These multipoles correspond to different kind of polarization pattern produced due to different types of perturbations; viz. scalar ($m = 0$), vector ($m = 1$), tensor ($m = 2$). Now, we will turn to one of the objectives of this article, getting a better understanding about these polarization patterns and their origin.

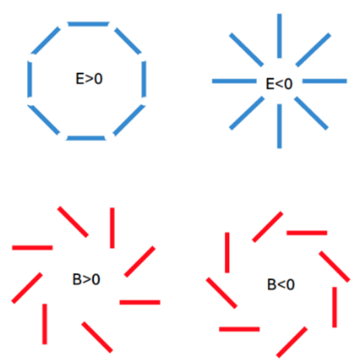


Figure 7: E and B modes of polarization (Image credits: [6])

Scalar Perturbations

These modes represent perturbations in the (energy) density of the cosmological fluid at last scattering and are the only fluctuations which can form structures through gravitational instability.

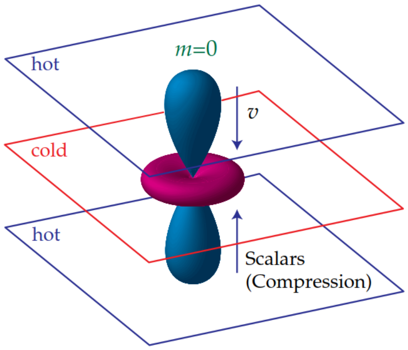


Figure 8: Polarization from Scalar Perturbations (Image credits: [5])

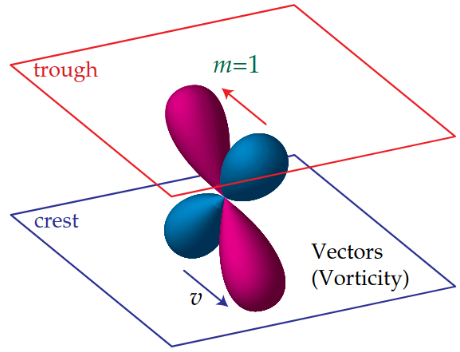


Figure 9: Polarization from Vector Perturbations (Image credits: [5])

Photon originating from a region having high matter-energy density will have to climb the gravitational potential well, eventually losing energy and appearing cold. Therefore, the hot regions are the regions of higher effective temperature (i.e., after taking potential into account also) and cold ones of lower, and at the scale where gravity dominates, matter (and photons) moves towards the cold region. This becomes the case of adiabatic fluctuations. We will represent the Temperature field as a Fourier expansion, giving us the intuition of the movement of the field, denoted by the wavevector k, with planewave basis. Considering only one Fourier component of this expansion, imagine an observer at the trough of the wave, i.e. at the "cold-plane" (see Figure 8). Remember that matter and photons are still coupled. The azimuthal symmetry in the problem requires that $v||k$ and hence the flow is irrotational $\nabla \times v = 0$. Because hotter photons from the crests flow into the trough from the $\pm k$ directions while cold photons surround the observer in the plane, the quadrupole pattern seen in a trough has an $m = 0$ structure. Mathematically,

$$Y_2^0 \propto 3cos^2(\theta) - 1$$

where $\theta = \hat{n} \cdot k$. Given the irrotational condition, scalar perturbations can't produce B-modes. As an interesting exercise, you can try to (qualitatively) prove that the polarization, in this case, would be either parallel or perpendicular to the direction of propagation of of the wave. Nature of the modes in Figure 7 follows from this conclusion, that for a wavevector originating from the center (of the patterns) and pointing radially outwards, the E modes will be either parallel or perpendicular to it, while B mode being at an angle of 45°. It is also important to note that the largest polarization signal occurs at the peaks of the temperature signal, so scalar perturbations produce a non-zero correlation between the temperature and polarization anisotropies.

Vector Perturbations

Vector perturbations represent vortical motions of the matter, where the velocity field v obeys $\nabla \cdot v = 0$ and $\nabla \times v \neq 0$. For a plane wave perturbation, the velocity field $v \perp k$ with direction reversing in crests and trough. The radiation field at these extrema possesses a dipole pattern due to the Doppler shift from the bulk motion. Quadrupole variations vanish here but peak between velocity extrema. To see this, imagine sitting between crests and troughs. Looking up toward the trough, one sees the dipole pattern projected as a hot and cold spot across the zenith; looking down toward the crest, one sees the projected dipole reversed. The net effect is a quadrupole pattern in temperature with $m = \pm 1$,

$$Y_2^{\pm 1} \propto sin(\theta)cos(\theta)e^{\pm i\phi}$$

The lobes are oriented at 45° from k and v since the line of sight velocity vanishes along k and at 90° to k here. The latter follows since midway between the crests and troughs v itself is zero.The polarization produced will be largest at the nulls and at an angle ±45° to the wave direction. A key difference to the last case is that while gravity amplifies scalar perturbations, any vector perturbations will decay in an expanding universe as the inverse square of the scale factor.

Tensor Perturbations

Tensor fluctuations are transverse-traceless perturbations to the metric, which can be viewed as gravitational waves. A plane gravitational wave perturbation represents a quadrupolar "stretching" of space in the plane of the perturbation. Consider a circular group of test particles with a gravitational wave propagating in the y-direction normal to the xz-plane of the circle. The + polarization alternately compresses and stretches the spacetime in horizontal and vertical directions causing the circle to be alternately elongated in top-to-bottom and side-to-side directions. The × polarization distorts the spacetime in a 45° alignment with respect to the + polarization. The rarefication and compression of the spacetime translates to redshift and blueshift of the photons in these directions, representing a temperature quadrupole moment with $l = 2, m = 2$,

$$Y_2^{\pm 2} \propto sin^2(\theta)e^{\pm 2i\phi}$$

The largest polarization signal will be seen by an observer whose line of sight is parallel to the wave direction. A major thrust of current research is to search for these inflationary gravitational waves.

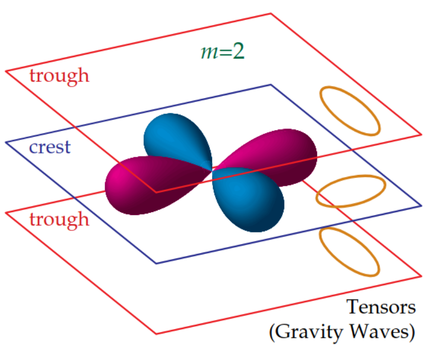
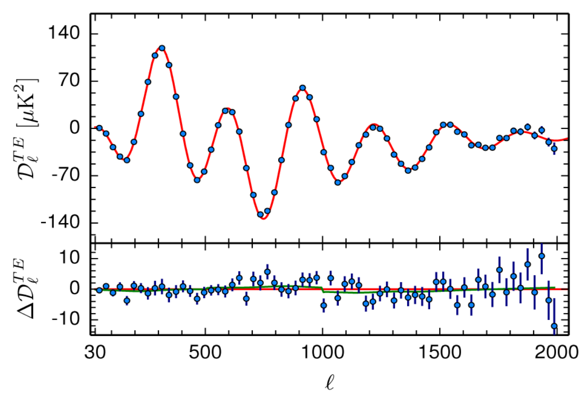


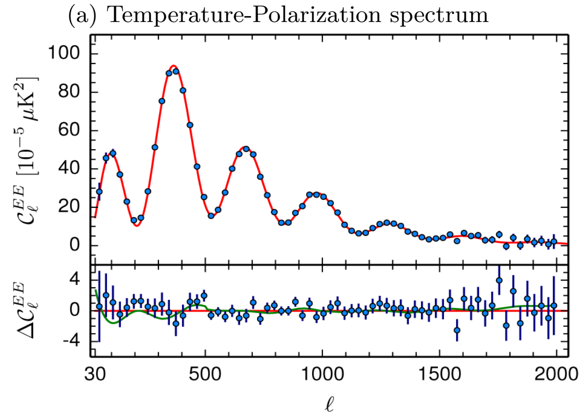
Figure 10: Polarization from Tensor Perturbations (Image credits: [5])

What lies ahead?

Any cosmological model will predict a particular power spectrum and a comparison with the actual one obtained can help us determine certain parameters or provide constraints which are crucial to test the validity of that model. Angular power spectrum depicts how a parameter changes across (a neighboring part of) the sky. For eg, if I move my detector a little bit away from a particular patch, I can use correlations to determine the change in the value of that parameter. These correlations are described as angular power spectrum. Figure 11 is the result from PLANCK (2015) and the fitting has been done according to the ΛCDM model, which shows its consistency. While scalar perturbations can't produce B modes, vector and tensor ones can, and due to the reasons mentioned previously, tensor ones are quite dominant. They tell us about the primordial gravitational waves, which can be further used to extract a lot of information in many areas of physics. For eg, tensor perturbations are often linked to different theories of quantum gravity and, therefore, the early universe has been transformed into a laboratory to test these theories. Lastly, it should be mentioned that B modes can also be generated via effects like Gravitational Lensing (although this is scale dependent, see Figure 12). Readers are encouraged to read more about this.



(a) Temperature-Polarization spectrum



(b) Polarization-Polarization spectrum

Figure 11: Angular Power Spectrum (Credits: [9])

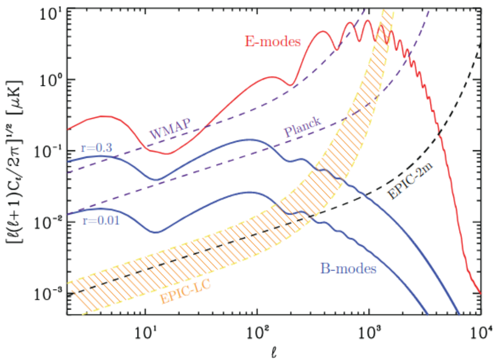


Figure 12: E and B mode power spectra for a tensor-to-scalar ratio saturating current bounds, r = 0.3, and for r = 0.01. Dotted lines are the experimental sensitivities of the instruments. (Credits: [10])

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Kaluza Klein Theory

Mainak Chandra, Writipriya Paul, Sriraj Chandra

The theory was introduced by Theodor Kaluza in his paper sent to Albert Einstein in 1919. Later presented by Einstein himself in 1921, Kaluza's paper attempted a straightforward extension of Einstein's four dimensional theory to five dimensions, to unify gravitation and electromagnetism - the two fundamental forces known at the time. He introduced the "cylinder condition" hypothesis that none of the physical/geometric quantities depend on the fifth coordinate. In 1926, Oskar Klein suggested that the fifth dimension is curled up and microscopic, which naturally justified the cylinder condition.

Gravitation and electromagnetism

General relativity and classical electrodynamics look different in terms of their mathematical formulations, but one can hope to unify them at the weak-field limit of Einsteinian relativity. Similar to the gauge invariance symmetry of Maxwell's equations, Einstein's equations show a very similar symmetry (invariance under infinitesimal coordinate transformations).

Classical electromagnetism

$$A_\mu \to A_\mu - \partial_\mu \Lambda \tag{5}$$

$$F_{\mu\nu} \to F_{\mu\nu} \tag{6}$$

General relativity

$$x^\mu \to x^\mu + \varepsilon^\mu \tag{7}$$

(infinitesimal coordinate transformations)
The metric is given by

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \tag{8}$$

where $\eta_{\mu\nu}$ is the Minkowski Metric, to which the perturbation term is added, and

$$h_{\mu\nu} \to h_{\mu\nu} - (\partial_\mu \varepsilon_\nu + \partial_\nu \varepsilon_\mu) \tag{9}$$

$$R^\mu_{\nu\rho\sigma} \to R^\mu_{\nu\rho\sigma} \tag{10}$$

The five-dimensional spacetime and gauge invariance

Consider the five dimensional analogue to the spacetime manifold, where every point is denoted by $x = (x^\mu, y) = (x^0, x^1, x^2, x^3, y)$ where (x^0, x^1, x^2, x^3) is the standard 4-D spacetime coordinate, and y is the additional fifth coordinate.
Consider the following coordinqte transformation,

$$\varepsilon^\mu = \varepsilon^\mu(x^0, x^1, x^2, x^3) \tag{11}$$

for $\mu = (0, 1, 2, 3)$

$$\varepsilon^5 = l\Lambda(x^0, x^1, x^2, x^3) \tag{12}$$

Λ is the scalar field reminiscent of the same symbol discussed with respect to gauge invariance, The length parameter l is added to ensure dimensional correctness.
As $\partial_5 \varepsilon^\mu = 0$, We have

$$h_{\mu 5} \to h_{\mu 5} - \partial_\mu \varepsilon_5 = h_{\mu 5} - l\partial_\mu \Lambda \tag{13}$$

To generate the gauge symmetry we are targetting, set

$$h_{\mu 5} = lA_\mu \tag{14}$$

for $\mu = 0, 1, 2, 3$. Again, l is added because A_μ has dimensions of inverse-length. With this, one obtains gauge invariance from coordinate invariance of GR.

Now, with cues from the above observation, we look at the following 5-dimensional metric.

$$\tilde{g}_{MN} = \begin{bmatrix} \eta_{\mu\nu} & lA_\mu \\ lA_\nu & 1 \end{bmatrix} \tag{15}$$

The Kaluza-Klein action and electromagnetism

Now, the next step would be to write down an analogue of the Einstein-Hilbert action in 5D, which turns out to be pretty straightforward.

$$S_{EH} = M_P^2 \int d^4x \, R\sqrt{-g} \quad , \quad S_{KK} = M_5^3 \int d^5x \, \tilde{R}\sqrt{-\tilde{g}} \tag{16}$$

Here, M_P is the Planck mass. M_5 is the analogous constant with inverse-length dimensions. The term is cubed to make the action dimensionless, similar to why Planck mass is squared in the Hilbert action.
Now, a detailed calculation involving Christoffel symbols gives

$$\tilde{R} = -\frac{1}{4} l^2 F^{\mu\nu} F_{\mu\nu} \tag{17}$$

Also,

$$\sqrt{-\tilde{g}} = 1 \tag{18}$$

Now, Klein's hypothesis restricts the values the fifth coordinate y can take. The dy integral hence boils down to a multiplicative $2\pi a$ factor (This comes from the fact that the y coordinate is curled up to form a circle of radius a.). Hence,

$$S_{KK}^{flat} = 2\pi a M_5^3 l^2 \int -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} d^4x \tag{19}$$

Even without going into tedious calculations, this can be written down from the following properties:

- As the metric was written from gauge invariance, the action should also be gauge invariant.
- Also, as the metric is $\eta_{\mu\nu}$, Lorentz invariance should be guaranteed.

It is known from classical electromagnetism that $F_{\mu\nu}F^{\mu\nu}$ is the only non-trivial term satisfying the requirements. The numerical factors can be found only from detailed calculations, which we skip. Now, comparing S_{KK} with the Maxwell action, the optimal values of l and a should satisfy

$$2\pi a l^2 M_5^3 = 1 \tag{20}$$

Lorentz force and equations of motion

Now, to get corresponding equations of motion, one looks at the particle action,

$$S_{particle} = -m \int [-g_{\mu\nu} dx^\mu dx^\nu]^{1/2} \tag{21}$$

where $\mu, \nu = 0, 1, 2, 3, 4$. This can be rewritten as,

$$-m \int [-\eta_{\mu\nu} dx^\mu dx^\nu + (dy + lA_\mu dx^\mu)^2]^{1/2} \tag{22}$$

Here, $\mu, \nu = 0, 1, 2, 3$.
Writing the Euler Lagrange Equation with respect to y,

$$\frac{d}{d\tau}\left(\frac{dy}{d\tau} + lA_\mu \frac{dx^\mu}{d\tau}\right) = 0 \tag{23}$$

One can easily identify the term as the conserved momentum in the y direction.

$$p = \frac{dy}{d\tau} + lA_\mu \frac{dx^\mu}{d\tau} \tag{24}$$

$$\frac{dp}{d\tau} = 0 \tag{25}$$

Writing the Euler Lagrange Equations with respect to the coordinate x^μ gives,

$$\frac{d}{d\tau}\left(-\eta_{\mu\nu} m \frac{dx^\mu}{d\tau} + plA_\nu\right) = pl\partial_\nu A_\lambda \frac{dx^\lambda}{d\tau} \tag{26}$$

$$\Rightarrow m\frac{d^2x^\mu}{d\tau^2} = plF^\mu_\nu \frac{dx^\nu}{d\tau} \tag{27}$$

This looks similar in structure to the Lorentz force equations,

$$m\frac{d^2x^\mu}{d\tau^2} = q\, F^\mu_\nu \frac{dx^\nu}{d\tau} \tag{28}$$

Comparing (23) and (24), one gets

$$pl = q \tag{29}$$

Compactification and charge quantization

In classical theory, p can take any value, but in quantum theory, the cylinder condition (periodicity) of space guarantees the quantization of momentum (p). Using the translation operator from quantum mechanics, the Klein's cylinder hypothesis translates to

$$e^{-\frac{ipy}{\hbar}} = e^{-\frac{ip(y+2\pi a)}{\hbar}} \tag{30}$$

$$\Rightarrow 2\pi ap = 2n\pi\hbar \qquad n = 0, 1, 2, .. \tag{31}$$

$$\Rightarrow q = \frac{n\hbar l}{a} \tag{32}$$

This is the familiar charge quantization result that emerged miraculously as a result of the Klein's hypothesis. The fundamental charge e in physics could be set as the value l/a taking units such that $\hbar = 1$.

$$\frac{l}{a} = e \tag{33}$$

The Kaluza-Klein metric

Now, the metric $\tilde{g}_{MN}$ can be extended in the most natural way to unify electromagnetism and general relativity.

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu + (dy + lA_\mu dx^\mu)^2 \tag{34}$$

Writing $dy = ad\theta$,

$$\Rightarrow ds^2 = g_{\mu\nu}dx^\mu dx^\nu + a^2(d\theta + eA_\mu dx^\mu)^2 \tag{35}$$

This gives

$$\tilde{g}_{MN} = \begin{bmatrix} g_{\mu\nu} & lA_\mu \\ lA_\nu & 1 \end{bmatrix} \tag{36}$$

The new Ricci scalar is given by

$$\tilde{R} = R(g) - \frac{1}{4}l^2 F^{\mu\nu}F_{\mu\nu} \tag{37}$$

Also,

$$\sqrt{-\tilde{g}} = \sqrt{-g} \tag{38}$$

Finally, we get,

$$S_{KK} = M_5^3 \int d^5x\, \sqrt{-g}\left(R - \frac{1}{4}l^2 F^{\mu\nu}F_{\mu\nu}\right) \tag{39}$$

$$= 2\pi a M_5^3 \int d^4x R\sqrt{-g} - 2\pi a M_5^3 l^2 \int d^4x \frac{1}{4}F^{\mu\nu}F_{\mu\nu} \tag{40}$$

To generate the Einstein-Hilbert action, the constants should satisfy

$$2\pi a M_5^3 = M_P^2 \tag{41}$$

Hence, using (16),

$$(M_P l)^2 = 1 \tag{42}$$

$$\Rightarrow l = l_p \tag{43}$$

where l_p is the Planck Length. In natural units, $e \simeq 0.3$. From (29), $l/a = e$ in natural units. Hence, $a \sim 3l_p$. This guarantees that the cylinder the space is curled up into, is microscopic. As the Planck length is the smallest length scale that can be constructed from the fundamental constants, this explains why higher dimensional effects do not show up in observations and experiments.

The dilaton and the Kaluza-Klein field equations

The "a" in the metric is a parameter which can be extended to a scalar field (the "dilaton"), leading to a metric,

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu + \phi(x)^2(d\theta + eA_\mu dx^\mu)^2 \tag{44}$$

$$\tilde{g}_{MN} = \begin{bmatrix} g_{\mu\nu} + e^2\phi^2 A_\mu A_\nu & e\phi^2 A_\mu \\ e\phi^2 A_\nu & \phi^2 \end{bmatrix} \tag{45}$$

Absorbing the coupling constant e into the potential term, we get,

$$\tilde{g}_{MN} = \begin{bmatrix} g_{\mu\nu} + \phi^2 A_\mu A_\nu & \phi^2 A_\mu \\ \phi^2 A_\nu & \phi^2 \end{bmatrix} \tag{46}$$

With this,

$$S_{KK} = \int M_p^2 R\phi\sqrt{-g}\, d^4x - \int \frac{1}{4}\phi^3 F^{\mu\nu}F_{\mu\nu}\sqrt{-g}\, d^4x - 2\pi a \int \partial^\alpha\phi\partial_\alpha\phi\sqrt{-g}\, d^4x \tag{47}$$

The first two terms are the Einstein-Hilbert and the Maxwell actions respectively (assuming ϕ is slowly varying). The third term is the kinetic part of the free scalar field (massless) action.

One usually considers a 5D vacuum to be such that the 5D energy-momentum tensor is 0, i.e. $\tilde{T}_{\mu\nu} = 0$

$$\Rightarrow \tilde{R}_{\mu\nu} = \frac{1}{2}\tilde{R}\tilde{g}_{\mu\nu} \tag{48}$$

$$\Rightarrow \tilde{R}_{\mu\nu} = 0 \tag{49}$$

$$\tilde{R}^{5\mu} = 0 \quad \Rightarrow \quad \nabla_\nu(\phi^3 F^{\mu\nu}) = 0 \tag{50}$$

Again, a slowly varying ϕ leads to,

$$\nabla_\nu F^{\mu\nu} = 0 \tag{51}$$

which constitute Maxwell's equations for curved spacetime. Also,

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{1}{2}M_p^{-2}\phi^2 T_{\mu\nu} \tag{52}$$

(assuming slowly varying ϕ with vanishing derivatives) where,

$$T_{\mu\nu} = \frac{1}{4}g_{\mu\nu}F^{\alpha\beta}F_{\alpha\beta} - F^{\alpha}_{\mu}F_{\nu\alpha} \tag{53}$$

is the energy-momentum tensor for the corresponding electromagnetic field.

Scalar field as a feature of Brans–Dicke theory

If a scalar field shows up in a four dimensional theory, experience suggests checking whether an extra dimension has leaked into the room. The presence of a nonminimally coupled scalar field in the Brans–Dicke action isn't just an arbitrary twist to general relativity. Instead, it's a natural, almost inevitable feature that emerges when we try to unify forces by adding extra dimensions. Any time you compactify a higher-dimensional gravitational theory down to our four-dimensional universe, you're left with leftover scalar fields, often called moduli. These fields describe the geometry of the hidden internal dimensions, like their size or shape, and they inherently couple to the 4D Ricci scalar in a specific way. This process automatically generates an effective scalar-tensor theory of the Brans-Dicke type.

A classic example is the Kaluza-Klein reduction of pure five-dimensional general relativity, which directly produces a Brans-Dicke action with the parameter $\omega = -1$ (see, e.g., the foundational work on this reduction). This allows a geometric interpretation of the Brans–Dicke scalar: it can be viewed as a radion field, a scalar degree of freedom that encodes the dynamical size of extra spatial dimensions.

What's fascinating is that this isn't just a quirk of simple models. The same pattern appears at the forefront of fundamental physics. In perturbative string theory, the dilaton field that determines the string coupling constant manifests in four dimensions precisely as a Brans–Dicke scalar. Similarly, in M-theory, the radion measuring the radius of the eleventh dimension plays an identical role. Across these frameworks, the Brans–Dicke scalar consistently emerges as the low-energy remnant of higher-dimensional geometry. The following section delves into the details of this profound connection.

Mathematical framework

In *scalar-tensor theories of gravity*, which extend general relativity by supplementing the spacetime metric $g_{\mu\nu}$ with an additional scalar degree of freedom ϕ, the same physical system can be described in two conformally related formulations known as the *Jordan frame* and the *Einstein frame*. In the Jordan frame, the scalar field is *non–minimally coupled* to gravity, meaning that it multiplies the Ricci scalar R in the gravitational Lagrangian, while all matter fields are *minimally coupled* to the metric $g_{\mu\nu}$. As a consequence, the matter Lagrangian is independent of ϕ, ensuring that freely falling test particles follow geodesics of the spacetime metric and that the *Weak Equivalence Principle*, the universality of free fall independent of internal composition, is satisfied. The Einstein frame is obtained from the Jordan frame by a *conformal (Weyl) rescaling* of the metric,

$$g_{\mu\nu} \longrightarrow \tilde{g}_{\mu\nu} = \Omega^2(\phi)\, g_{\mu\nu},$$

together with a redefinition of the scalar field chosen so that the gravitational part of the action reduces to the standard Einstein–Hilbert form, i.e. the action used in general relativity where the Ricci scalar R appears linearly and the scalar field has a canonical kinetic term of the form $\frac{1}{2}(\partial\phi)^2$. In this formulation, the spacetime metric no longer couples directly to matter alone; instead, matter fields acquire explicit dependence on the scalar field as well. Physically, this means that in addition to the usual gravitational interaction described by the metric, test particles experience an extra force sourced by the scalar field. Consequently, particle trajectories are no longer determined solely by the spacetime geometry and do not coincide with geodesics of the Einstein-frame metric. If the scalar field couples differently to different types of matter, this additional force acts unequally on different test bodies, leading to violations of the Weak Equivalence Principle.

In the Jordan frame, the Brans–Dicke Lagrangian density is given by

$$\mathcal{L}_{BD} = \sqrt{-g}\left(\phi R - \omega\frac{1}{\phi}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + \mathcal{L}_{\rm matter}\right), \quad (54)$$

where ϕ is the Brans–Dicke scalar field (interpreted as $G_{\rm eff}^{-1}$), ω is the coupling parameter, and $\mathcal{L}_{\rm matter}$ is the matter Lagrangian, which is independent of ϕ so as to preserve the Weak Equivalence Principle. The energy–momentum tensor of matter is defined by

$$T_{\mu\nu} \equiv -\frac{2}{\sqrt{-g}}\frac{\delta(\sqrt{-g}\,\mathcal{L}_{\rm matter})}{\delta g^{\mu\nu}}. \quad (55)$$

Varying the action with respect to the spacetime metric $g_{\mu\nu}$, we use the standard variational identity

$$\delta(\sqrt{-g}\,R) = \sqrt{-g}\left(G_{\mu\nu}\,\delta g^{\mu\nu} + \nabla_\alpha V^\alpha\right),$$

where the vector V^α arises from the variation of the Levi–Civita connection and is defined as

$$V^\alpha \equiv g^{\mu\nu}\,\delta\Gamma^\alpha_{\mu\nu} - g^{\alpha\mu}\,\delta\Gamma^\nu_{\mu\nu}.$$

In general relativity the divergence term $\nabla_\alpha V^\alpha$ contributes only a boundary term to the action and may be discarded under suitable boundary conditions. In Brans–Dicke theory, however, this term appears multiplied by the scalar field ϕ and therefore cannot be neglected. Integrating by parts instead produces additional contributions involving derivatives of ϕ. Taking these terms into account, the variation of the action yields the metric field equations

$$\phi\,G_{\mu\nu} = T_{\mu\nu} + \frac{\omega}{\phi}\left(\partial_\mu\phi\,\partial_\nu\phi - \frac{1}{2}g_{\mu\nu}(\partial\phi)^2\right) + \nabla_\mu\nabla_\nu\phi - g_{\mu\nu}\Box\phi, \quad (3)$$

where $T_{\mu\nu}$ is the stress–energy tensor of matter and $\Box \equiv g^{\mu\nu}\nabla_\mu\nabla_\nu$ denotes the covariant d'Alembertian operator.

Variation of the action with respect to ϕ gives

$$R - \omega\frac{1}{\phi^2}(\partial\phi)^2 + 2\omega\,\frac{1}{\phi}\Box\phi = 0. \quad (56)$$

Taking the trace of and combining it with (56) eliminates R, leading to the scalar field equation

$$\Box\phi = \frac{8\pi}{2\omega+3}T, \quad (57)$$

where $T = T^\mu{}_\mu$ is the trace of the matter stress–energy tensor.

Brans Dicke field equations

Thus, the Brans–Dicke theory in the Jordan frame is governed by

$$\boxed{\begin{aligned} G_{\mu\nu} &= \frac{T_{\mu\nu}}{\phi} + \frac{\omega}{\phi^2}\left(\partial_\mu\phi\,\partial_\nu\phi - \frac{1}{2}g_{\mu\nu}(\partial\phi)^2\right) \\ &\quad + \frac{1}{\phi}\left(\nabla_\mu\nabla_\nu\phi - g_{\mu\nu}\Box\phi\right), \\ \Box\phi &= \frac{8\pi}{2\omega+3}T. \end{aligned}} \quad (58)$$

The Brans–Dicke parameter ω measures the strength of the scalar component in the gravitational interaction. From the action.

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\left(\phi R - \frac{\omega}{\phi}\,\partial_\mu\phi\partial^\mu\phi\right) + S_m, \quad (59)$$

the scalar-field equation follows as

$$\Box\phi = \frac{8\pi}{3+2\omega}T, \quad (60)$$

showing that matter sources variations of ϕ with an amplitude proportional to $(3+2\omega)^{-1}$. Hence the scalar field becomes progressively weaker as ω grows.

In the limit $\omega \to \infty$, we have $(3+2\omega)^{-1} \to 0$, so $\Box\phi \to 0$. Astrophysical boundary conditions then force ϕ to approach a constant $\phi_0 = G^{-1}$, and substituting this into the action yields the Einstein–Hilbert action. Thus, Brans–Dicke gravity contains general relativity as the limiting case in which the scalar field decouples.

Solar-system experiments constrain any departure from GR by probing post-Newtonian parameters. Especially, the Cassini measurement of the Shapiro time delay (2003) gives

$$\omega \gtrsim 4 \times 10^4, \tag{61}$$

a stronger bound than the earlier ones (e.g., Viking $\omega \gtrsim 10^3$). Thus, any scalar degree of freedom present today must be extremely weak, though it could have played a significant role in the early universe.

Physical predictions and tests

For cosmological applications it is convenient to work in the Einstein frame, which is obtained from the Jordan frame by a Weyl (conformal) rescaling of the metric followed by a field redefinition that renders the scalar kinetic term canonical. We denote the resulting Einstein-frame scalar field by σ. In this frame, the Friedmann equation takes the form

$$3H^2 = \rho_m + \rho_\sigma, \qquad \rho_\sigma = \frac{1}{2}\dot{\sigma}^2 + V(\sigma), \tag{10}$$

where the scalar potential is of exponential form,

$$V(\sigma) = \Lambda e^{-4\zeta\sigma}. \tag{62}$$

Fujii and Maeda show that such a potential produces a characteristic sequence of phases: an initial *kinetic–term–dominated era* ($\frac{1}{2}\dot{\sigma}^2 \gg V$), followed by strong Hubble friction that damps $\dot{\sigma}$, after which the field enters a temporary *hesitation (or plateau) phase* where $\dot{\sigma} \approx 0$ and

$$\rho_\sigma \simeq V(\sigma) \approx \text{const.}, \qquad a(t) \propto t^p, \quad p > 1. \tag{63}$$

During this interval, the universe undergoes accelerated expansion, even though no true cosmological constant is present. As matter density decreases as $\rho_m \propto a^{-3}$, the condition $\rho_m \sim \rho_\sigma$ is eventually met; the potential force then drives σ away from the plateau and acceleration ends. Hence the present acceleration is interpreted as a transient episode of "mini–inflation," occurring naturally when $\rho_m(t)$ becomes comparable to $V(\sigma)$, without fine tuning.

For massless Brans–Dicke theory, Hawking's 1972 result demonstrates that stationary black-hole solutions are indistinguishable from those of general relativity. The proof relies on the scalar-field equation in vacuum,

$$\Box\phi = 0, \tag{64}$$

together with the assumption of asymptotic flatness and regularity at the event horizon. Integrating the scalar equation over the black-hole exterior and applying Gauss's theorem yields

$$\int_\Sigma (\nabla\phi)^2 \, d^3x = 0, \tag{65}$$

implying $\nabla_\mu \phi = 0$ everywhere outside the horizon and hence $\phi = \phi_0 = \text{const.}$ The field equations then reduce exactly to the vacuum Einstein equations. Thus every stationary black hole in massless Brans–Dicke gravity is described by the Kerr–Newman family, i.e., it possesses no "scalar hair". This result explains why astronomical black-hole observations (e.g., ringdown spectra, shadow images) do not currently differentiate between Brans–Dicke theory and general relativity. The scalar field can drive cosmological dynamics on large scales yet remains effectively "screened" in strong-field, horizon-containing configurations, thereby restoring general relativity near astrophysical compact objects. The no-hair theorem therefore plays a crucial role in maintaining the empirical viability of Brans–Dicke theory despite its additional degree of freedom.

The post-Newtonian expansion provides a quantitative framework for testing gravity in the weak-field, slow-motion regime. In Brans–Dicke theory, the parametrized post-Newtonian (PPN) coefficients acquire explicit dependence on the parameter ω. Most relevant is the space-curvature parameter

$$\gamma = \frac{1+\omega}{2+\omega}, \tag{66}$$

which measures the amount of light deflection, Shapiro time delay, and perihelion advance predicted by the theory. General relativity corresponds to $\gamma = 1$, recovered only in the limit $\omega \to \infty$. Solar system measurements therefore serve as direct constraints on ω via high-precision determinations of γ. Early radar-ranging experiments already imposed $\omega \gtrsim 10^2$, later improved by very-long-baseline interferometry to $\omega \gtrsim 10^3$. The most stringent bound comes from the Cassini spacecraft measurement of the Shapiro delay, which gives

$$\gamma - 1 = (2.1 \pm 2.3) \times 10^{-5} \quad \Rightarrow \quad \omega \gtrsim 4 \times 10^4. \tag{67}$$

These results imply that the scalar sector must be extremely weak today, forcing Brans–Dicke gravity to behave almost identically to general relativity in the solar system. Nevertheless, cosmological and early-universe environments remain less constrained, leaving open the possibility of significant scalar dynamics on large scales.

The joint observation of GW170817 and the gamma-ray burst GRB 170817A marks a crucial turning point for tests of gravity. The arrival times of gravitational and electromagnetic signals agree to within parts in 10^{15}, implying that the propagation speed of gravitational waves satisfies

$$\left|\frac{c_{\rm GW}}{c} - 1\right| \lesssim 10^{-15}. \tag{68}$$

Ezquiaga and Zumalacárregui (2017) showed that this single measurement rules out large classes of scalar–tensor theories whose dynamics modify the effective tensor speed, most notably those with derivative couplings of the form $G_5(\phi, X)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi$ in the Horndeski Lagrangian. By contrast, Brans–Dicke theory with a canonical kinetic term keeps $c_{\rm GW} = c$ and is therefore consistent with the multi-messenger bound. The result dramatically reshapes the landscape of modified gravity: compatibility with gravitational-wave propagation now requires that late-time cosmic acceleration cannot arise from nonstandard tensor dynamics but must instead be sourced by a scalar potential or conformal coupling. Consequently, scalar–tensor cosmology remains viable, but the "dark energy from modified gravity" paradigm has become significantly more restricted since GW170817.

Kaluza-Klein origin of Brans-Dicke theory

A direct theoretical origin of Brans–Dicke theory is obtained from pure five-dimensional general relativity compactified on a circle S^1. The Kaluza–Klein metric ansatz

$$ds^2_{(5)} = g_{\mu\nu}(x)\, dx^\mu dx^\nu + \phi(x) \left(dy + A_\mu(x)\, dx^\mu\right)^2, \tag{69}$$

splits the five-dimensional geometry into a four-dimensional metric $g_{\mu\nu}$, a vector field A_μ, and a scalar ϕ associated with the radius of the compact dimension. Dimensional reduction of the Einstein–Hilbert action

$$S_{(5)} = \frac{1}{16\pi G_{(5)}} \int d^5x \sqrt{-g_{(5)}}\, R_{(5)}, \tag{70}$$

leads to the four-dimensional effective action

$$S_{(4)} = \frac{1}{16\pi} \int d^4x \sqrt{-g} \left(\phi R - \frac{1}{\phi}(\partial\phi)^2 - \frac{1}{4}\phi F_{\mu\nu}F^{\mu\nu}\right), \tag{71}$$

which is exactly the Brans–Dicke Lagrangian with parameter $\omega = -1$. Thus the Brans–Dicke scalar ϕ is not an arbitrary new field: its magnitude measures the size of the compact extra dimension, and slow evolution of ϕ corresponds to a dynamical Newton constant in four dimensions.

In realistic KK cosmological models, additional bulk fields generate further KK excitations. The first excited KK scalar mode can behave as pressureless matter, while the coupling of ϕ to gauge fields can induce a late-time vacuum-dominated phase. Consequently, the dark matter–like and dark energy–like epochs arise not from exotic fluids but from relic KK modes inherited through dimensional reduction. The same geometric mechanism that yields the Brans–Dicke action with $\omega = -1$ can therefore also reproduce a unified dark sector (cold dark matter + cosmic acceleration), illustrating a deep link between extra dimensions and scalar–tensor cosmology.

String theory dilaton as a Brans–Dicke scalar

A unified theoretical origin of Brans–Dicke–type scalar fields arises naturally in perturbative string theory as well as in M–theory compactifications. At tree level, the low-energy effective action of closed strings contains, in addition to the spacetime metric $g_{\mu\nu}$, a universal scalar field known as the *dilaton*, denoted by Φ. In four dimensions, the string-frame action takes the form

$$S_{\rm str} = \frac{1}{2\kappa^2} \int d^4x \sqrt{-g}\, e^{-2\Phi} \left(R + 4(\partial\Phi)^2 - \frac{1}{12}H^2 + \cdots\right), \tag{72}$$

where $H_{\mu\nu\rho}$ is the field strength of the antisymmetric tensor field, the ellipsis denotes higher-order and matter contributions, and the exponential prefactor reflects the dependence of the string coupling constant, $g_s = e^\Phi$.

In this form, the dilaton multiplies the Ricci scalar R and therefore appears as a *non-minimally coupled* scalar field in the gravitational action. This structure is identical to that of a scalar–tensor theory of the Brans–Dicke type, with the dilaton playing the role of the Brans–Dicke scalar. In particular, comparing the gravitational sector of the string-frame action with the Brans–Dicke action shows that the effective Brans–Dicke parameter takes the value $\omega = -1$. Consequently, the dilaton controls the effective Newton constant in four dimensions, which becomes a spacetime-dependent quantity determined by the expectation value of Φ.

An equivalent geometric interpretation emerges in M–theory. Writing the eleven-dimensional metric in the form

$$ds^2_{11} = e^{-2\Phi/3} ds^2_{10} + e^{4\Phi/3}(dy)^2, \tag{73}$$

one finds that the radius of the compactified eleventh dimension depends on the scalar field as

$$R_{11}(x) \propto e^{2\Phi(x)/3}. \tag{74}$$

Fluctuations of the size of the internal circle therefore give rise to the same scalar degree of freedom $\Phi(x)$, which, upon dimensional reduction to four dimensions, appears as a non-minimally coupled scalar field multiplying the Ricci scalar. More generally, in compactifications on higher-dimensional internal manifolds, the overall volume modulus (the *radion*) enters the four-dimensional effective action in precisely this way.

Thus, both the dilaton of string theory and the radion of M–theory provide natural, geometric realizations of Brans–Dicke–type scalar fields. In each case, the scalar degree of freedom originates from higher-dimensional geometry and manifests in four dimensions as a scalar–tensor theory with $\omega = -1$, establishing a deep connection between extra dimensions and Brans–Dicke gravity.

Mass of fundamental particles

Next, let us consider the complex scalar field action in 5D flat spacetime.

$$S_{scalar} = -\int d^4x dy \, \sqrt{-\tilde{g}} \left(\tilde{g}^{AB} \partial_A \phi \, \partial_B \phi^\dagger + m^2 \phi^\dagger \phi \right) \tag{75}$$

where the metric from (11) is used.

$$\tilde{g}^{AB} = \begin{bmatrix} \eta^{\mu\nu} & -lA^\mu \\ -lA^\nu & 1 + l^2 A^\mu A_\mu \end{bmatrix} \tag{76}$$

We put in the Fourier expansion,

$$\phi(x^\mu, y) = \sum_n \varphi_n(x^\mu) e^{\frac{iny}{a}} \tag{77}$$

as the y coordinate is periodic. We get the action,

$$S = -2\pi a \sum_n \int d^4x \Bigg((\partial_\mu + ineA_\mu)\varphi_n^\dagger \eta^{\mu\nu} (\partial_\nu - ineA_\nu)\varphi_n + m_n^2 \varphi_n^\dagger \varphi_n \Bigg) \tag{78}$$

where,

$$m_n = \sqrt{m^2 + \left(\frac{n}{a}\right)^2} \tag{79}$$

m denotes then intrinsic mass of the scalar field (in 5D). This mass needs to be set to zero, as the five dimensional space is a mathematical construct; there is nothing physical in a 5D mass. Also, we obtained GR and Maxwell's Equations using the Vacuum Field Equations in 5D (44). Hence, it makes sense to set $m = 0$. Thus,

$$m_n = \frac{|n|}{a}$$

As $a \sim l_p$, $m_n \sim M_p$, for nonzero n. $M_p = 2.176 \times 10^{-8}$ kg. Through the calculation, we were trying to explain the mass associated with fundamental charged particles, but, the masses obtained are 10^{22} times larger than electron mass. Also, one hopes that different subatomic particles could be obtained by taking different modes (different values of n). The difference between masses in two different modes is of the order of $10^{-8} kg$ or 10^{19} GeV. For, comparison, the gap between electron and muon mass is of the order of 0.1 GeV. Thus, again the predictions are 20 orders of magnitude off. Hence, the resulting "Kaluza Tower" has zero mass for the $n = 0$ mode and very large mass for all other modes.

This is one of the major failures of the theory. Modern string theory tries to explain this by considering the $n = 0$ mode, and explaining the comparatively "tiny" masses of elementary particles by different "mechanisms".

Onward to stringy affairs

When Kaluza-Klein theory was proposed i.e., in the 1920s, the world of theoretical physics was extremely busy with quantum mechanics and particle physics. So, despite KK being a candidate to unify all known forces at that time, it was overshadowed by its more successful microscopic counterparts. It was an inherently classical theory with no easy quantum generalization. Also, as discussed above, even at the beginning, it had certain drawbacks, which were further increased by the discovery of the strong and the weak forces, which KK can't explain at all. Thus, it was left in the dust.

There was some intermediate work done to advance KK, such as Pauli's attempt to extend it to a non-Abelian gauge theory in 6 dimensions, from which he was able to arrive at various results in Yang-Mills theory before it was even formally discovered. However, this was kept unpublished as Pauli could not satisfy himself as to the particle masses predicted by his theory.

The emergence of string theory was a result of an inability to formulate a gravitational quantum field theory, which had been able to successfully tackle electromagnetic, strong and weak forces in the form of QED, QCD and QFD (which were unified later). It was then that compactification of extra dimensions was recalled to the arsenal of theoretical physicists, which became one of the principal ideas behind modern string theories, such as superstring theory which has 6 compactified dimensions and is a 10-dimensional theory overall. As is

unanimously held, string theory is currently the leading candidate for a theory of everything. There have been further generalizations of KK to higher dimensions, all of which are collectively referred to as **Kaluza-Klein theories**.
Although ignored at its time, Kaluza-Klein theory is an important predecessor to modern string theory through its fundamental idea of reproducing the standard forces through compactification of higher dimensions, a tool at the heart of modern theoretical physics.

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Optical Lattices: A Revolution in Physics

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A Brief History of 'Measuring' Time

"If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures, what statement would contain the most information in the fewest words? I believe it is the atomic hypothesis. . . "
Richard Feynman

Measurement of time has always been an inevitable factor for the mankind. Time helped us to understand our world more systematically. The Sun, the Moon, the Stars- gave us daily, monthly and seasonal aspects of time. The ability to keep time at ancient times enabled agriculture - the advent of civilisation. Day after day the world we see, we feel, changed a lot. Necessity of standardization of time grew bigger along with civilization across the globe. Sundials and water clocks were created to make life easier. Sand clocks (eg: hour glasses) and candle clocks and what not. As time progressed we became really concerned that the errors in these measurements are too much to reach the society's potential.

Later, mechanical clocks were developed in medieval Europe (1300 AD) and no sooner, created a significant impression. It marked hours with an accuracy of 15 minutes per day while the old techniques had errors on the scale of hours per day. Then, Huygen's pendulum (1656 AD) was an absolute revolution which marked an accuracy in seconds per day. It marked timekeeping in a very precise and scientific manner. Harrison's marine chronometer (1700 AD) powered the global navigation with an accuracy of a fraction of a second per day. After all these incredible changes, we witnessed a humongous leap in measurement of time in the 20th century. The story of time is evolving, along with sapiens; their needs, their knowledge.

Quartz clocks became world's most accurate clock in 20th century with an accuracy of seconds per year. It worked on the 'very stable' natural frequency of quarts crystals being held sacrosanct. Although it was quite accurate; factors like temperature, stress, aging of the crystal and defects made the crystals "drift" and led to relatively inaccurate measurement. In the mid-20th century, growth of radio communication, satellite navigation, and the scientific community's zeal to test the groundbreaking theory of relativity; demanded an ultra precise method for time measurement. All of these began with the experiments of an American physicist on atomic beam magnetic resonance in 1937, laying the foundations of early atomic clocks which allowed scientists to measure atomic transition frequencies with a magnificent accuracy. This pioneering work was done by Isaac Rabi and he got the Nobel Prize in physics in 1944, "for his resonance method for recording the magnetic properties of atomic nuclei". After 10 years of Rabi's experiment, US National Bureau of Standards (now NIST) appointed Harold Lyons to take the first step in turning theory of atomic clocks into a practical device. He chose 24 GHz resonance of nitrogen molecules to build the first atomic clock prototype in 1949.

It grabbed a world wide attention. At that time, NPL in England got a proposal. It was from a scientist who measured the speed of light with a record of nine digit precision. He wasn't impressed with Lyons' result. He observed that it's frequency is unstable and it could run only for a few hours at a time. He proposed to make a more practical and accurate atomic clock using an alkali metal, having a single stable isotope and a simple and narrow spectrum, resonating at a frequency that microwaves could match. Louis Essen chose Cesium. NPL accepted the proposal the next year when a new director came in charge. In the war-stricken Britain, he and a microwave expert Jack Parry spent long hours measuring electromagnetic fields and installing high vacuum equipment to contain the Cesium. Their key goal was an atomic clock able to operate for a long time with 'atomic' accuracy. In 1955, Essen and Parry became the basis for redefining the second; they built the first practical, accurate Cesium atomic clock. It became a revolutionary discovery in many ways which includes pushing of metrology towards atomic physics, laying foundations for modern optical atomic clocks, enabling development in GPS and redefined time standard in 1967.

The concept of optical lattice is a result of decades of progress in observations and experiments. An optical lattice is formed by the interference of counter propagating laser beams. As a result it creates a spatially periodic intensity pattern (can be visualised as an egg storage tray). It's one of the major foundations is Essen-Parry atomic clock itself. The separated oscillatory fields method by Norman Ramsey improved the precision of measurement of atomic transitions. He was awarded the 1989 Nobel Prize in Physics for this invention, called Ramsey interferometry. Development of ion trapping, laser cooling & trapping and optical frequency comb were the critical technological breakthroughs in the growth of research on optical lattices.

In 2001, Hidetoshi Katori proposed an idea of trapping thousands of neutral atoms in an optical lattice; which wasn't the usual one. This optical lattice is formed by the laser beams which have a specific wavelength – **magic wavelength**, which causes equal Stark shift of the ground and excited levels used for clock transition, leading to intensity independent invariant energy gap. He and Tetsuya Ido built the first true optical lattice clock prototype and it indisputably revolutionized the field. Later Jun Ye developed ultra precise lasers and enhanced precision spectroscopy while Andrew Ludlow led the development of the most accurate strontium lattice clocks.

Optical Lattices

The accuracy of a clock depends on the effects of electromagnetic perturbation and Doppler shift, and the stability of the clock. In the case of atomic clocks, ions are trapped in Paul traps, which confine them in the areas where electric field is zero, cancelling the energy shifts from both transition states and reducing electromagnetic perturbation. Doppler shift is also reduced since the confinement region of the ion is smaller than the transition wavelength. However, the stability of the atomic clock is limited by the quantum projection noise (QPN), which corresponds to the statistical uncertainty in measuring the excitation probability.

Optical lattice clocks use the concept of a magic wavelength to control these perturbations. Optical lattices are arrays of atoms trapped in periodic potentials, created by counter-propagating laser beams. Two laser beams interfere with each other to form standing waves. This creates a series of crests and troughs, where cooled-down atoms get trapped through the Stark shift. Stark shift refers to the splitting of spectral lines of atoms in the presence of an external electric field. This electric field turns the atom into a tiny dipole, which interacts with the field and causes a shift in the atomic energy. This value of potential is determined by the corresponding intensity at each point. The location of trapping (crest or trough) is determined by the wavelength of the laser beams used. Red-detuned light refers to the light at a frequency below the resonant frequency of the atoms, and it results in the trapping of atoms at intensity maxima. Blue-detuned light refers to the light above resonant frequency, and the trapping occurs at minima. With reference to making clocks, blue-detuned lattices are used to make the effects of higher order light shifts negligible, since the intensity is much less at nodes than at antinodes. When optical lattices for clocks were first proposed, however, red-detuned light was used, since the wavelength was low enough to allow light shifts to be insensitive to small errors in the lattice frequency, and resulted in high accuracy. Optical lattices for clocks are generally made using elements in groups II and IIB, like He, Be, Zn, Hg, etc. The first demonstration of magic lattices was done using 88Sr, with transition 1S0 to 3P1. A 1D array of tightly confined atoms were used, allowing for a 'Mössbauer spectrum'. In other words, the confinement of the atoms prevented any loss of energy due to recoiling, which in turn prevented broadening of the spectral lines (Doppler broadening).

Experimental Realisations

The 1S0 to 3P0 transition is doubly forbidden, due to change in total angular momentum and spin multiplicity. Thus, it is very hard to observe, resulting in a narrow spectral line. This narrowness makes it excellent for clock transitions as a frequency reference. Moreover, 3P0 is a metastable state, allowing for more precise measurements. To add to the excitation probability, hyperfine mixing of states is done with 3P0 and nearby states. This mixed state has some $J = 1$ character, which while negligible, allows for usage as clock transitions. The SYRTE group and the University of Tokyo group independently investigated this forbidden 1S0 to 3P0 transition in 87Sr, where line width reduction was observed at a certain frequency and the magic wavelength was, thus, determined. Further, in 2005, JILA/NIST, SYRTE and University of Tokyo groups performed absolute frequency measurements that demonstrated reproducibility and international consistency. This eventually led to the Bureau International des

Poids et Mesures (BIPM) recognising the Sr 1S0 to 3P0 optical lattice transition as the Secondary Representation of the Second (SRS) in October, 2006.

Multipolar interactions

When blue-detuned lattices are used, the atoms are trapped at the nodes of the standing wave. In this case, the presence of multipolar interactions must be considered. The magnetic dipole (M1) and electric quadrupole (E2) effects are largest at nodes (due to a phase difference compared to the electric dipole), thus dominating higher order light shifts. Although these interactions are tiny compared to the electric dipole interactions in the case of red-detuned lattices (where atoms sit at the antinodes), they are still comparatively significant in blue-detuned lattices and cause position-dependent light shifts. Thus, the usual definition of magic wavelength, that depends on cancelling E1 polarizabilities, becomes inadequate. In order to eliminate this dependence on atomic motional states, an extended definition of magic wavelength is required which incorporates all multipolar contributions. By employing a specific lattice geometry and electric field polarisation, all multipolar interactions can be made to share the same spatial dependence. Under these conditions, the magic wavelength can be defined independent of the atomic motion. The residual light shift becomes an extra offset term, which simply depends on the total lattice laser intensity, which can be measured.

Fermions and Bosons

Collisional frequency shifts are an important limitation in the design of optical lattice clocks, and they depend mainly upon the quantum statistics of the trapped particles and lattice geometry. For bosons, these collisional shifts are completely unavoidable. This is because due to the property of bosons that allow then to occupy the same motional and internal state. Thus, they experience s wave collisions even at ultracold temperatures. Fermions, on the other hand, obey Pauli's exclusion principle, as a result of which s-wave collisions are suppressed for ultracold spin-polarised fermionic gas. In 1D and 2D lattice geometries, atoms are only confined in transverse directions. In such cases, fermions still avoid occupying the same state, but bosons may overlap spatially, making fermions ideal for avoiding collisional shifts. In 3D lattices, both bosons and fermions are held in the lattice sites, which suppresses the collisional shift in both cases. However, 3D lattices introduce an additional complexity. 3D lattices are generated by multiple electric field vectors, each with different orientation and polarisation. Thus, cancelation of vector light shifts becomes more complicated due to all the different interactions between the magnetic states of atoms and the electric field polarisations. For fermions, total angular momentum (which interacts with the polarisation to cause vector light shifts) $F = I + J$ is non zero due to half integer nuclear spins, while for bosons, F can be zero due to integer nuclear spins. Thus, bosonic isotopes are found to be suitable in 3D lattices when using $J = 0$ transition states, to make $F = 0$ and make vector light shifts vanish.

Quantum Simulation using Optical lattice:

Atoms in optical lattices provide ideal quantum system where all parameters are highly controllable and where simplified models of condensed matter physics may be experimentally realised. Atoms can be imaged directly something which is difficult to do with electrons in solids.

The differing the number of beams and geometries, various lattice geometries can be created. The can range from simplest case of two counterpropagating beams forming a 1D lattice to a more complex geometries like hexagonal lattice. The vast variety of geometries that can be produced in optical lattices allow the realisation of complex systems like Bose Hubbard Model, the Kagome lattice and Sachdev Ye Kitaev model and the Aubrey Andre model. Studying evolution of atoms under the influence of these Hamiltonians may lead to the description of dynamics of electrons in various lattice models, insights about the solution of Hamiltonian may be gained.

Dawn of Optical Clocks

The optical lattice clock is a type of atomic clock that uses neutral atoms—typically alkali metals like Strontium or Ytterbium—confined within an optical lattice. The core "ticking" mechanism of the clock is an ultra-narrow optical transition frequency. This frequency oscillates at hundreds of terahertz (hundreds of trillions of cycles per second), vastly higher than the microwave frequencies used in traditional standards like the cesium fountain clock. According to fundamental physics, a faster "tick" translates directly to greater potential precision.

The concept originated in 2001 at the University of Tokyo, proposed by Hidetoshi Katori. Katori recognized that trapping neutral atoms in a laser lattice at a specific "magic wavelength" could provide a superior frequency reference.

How to Cook an Optical Clock

Creating an optical lattice clock involves a sophisticated three-step process: cooling, trapping, and probing.

Before atoms can be trapped, they must be slowed down to reduce thermal noise. This involves cooling them to incredibly low temperatures, often just a fraction of a degree above absolute zero (near the nano-Kelvin range). Scientists achieve this using techniques like Doppler cooling and, subsequently, Raman sideband cooling.

Once cooled, the atoms are loaded into the optical lattice. This lattice is not a physical container but a structure made entirely of light, created by intersecting laser beams.

When multiple laser beams overlap, they form a standing wave pattern that generates a periodic, three-dimensional array of tiny potential energy wells—tiny "buckets" of light as discussed.

These wells hold neutral atoms in a crystal-like arrangement. Unlike single-ion clocks, an optical lattice clock can trap millions of atoms simultaneously. Interrogating such a vast ensemble allows for averaging that drastically reduces "quantum projection noise," a measurement uncertainty inherent to quantum systems, thereby significantly improving stability.

With atoms securely held, a separate probe laser—acting as the clock's pendulum—is shone onto them. This laser is tuned to the specific frequency required to excite the atoms from their ground state to a long-lived excited state. This optical transition frequency serves as the central oscillation of the clock.

The Optical Frequency Comb

Because the optical clock ticks at hundreds of trillions of cycles per second, standard electronic counters cannot track it. The solution is the optical frequency comb.

This device acts as a "reduction gear" or frequency divider. It produces a spectrum of ultra-sharp, evenly spaced frequency lines that resemble the teeth of a comb. By bridging the gap between the ultra-fast optical domain and the slower microwave domain, the comb translates the fundamental quantum oscillations into a countable signal that standard electronics can process.

Optical Lattices vs. Ion Traps

While optical lattice clocks use neutral atoms, another leading technology uses ion traps (specifically Paul traps).

Ion Traps (Paul Traps): These systems trap charged particles using oscillating radio-frequency (RF) electric fields. Because charged particles repel each other via Coulomb force, these traps often hold only a *single* ion to avoid disturbance. While this single ion is incredibly isolated—ideal for quantum computing—it lacks the stability benefits of averaging millions of atoms. Micromotion: A unique disadvantage of ion traps is "micromotion," where the ion jitters at the RF drive frequency, potentially introducing errors.

The Physics of Manipulation: Red vs. Blue Detuning

The ability to trap or repel atoms relies on "detuning"—the precise mismatch between the laser's color and the atom's natural resonance.

- **Red Detuning:** When the laser is tuned slightly *below* resonance, it acts as an attractive force (a "siren song"), drawing atoms toward the beam's brightest point to freeze them in place.
- **Blue Detuning:** When tuned slightly *above* resonance, the light becomes repulsive, pushing atoms away from high-intensity areas and herding them into dark cages.

By toggling between these modes, physicists can sculpt invisible landscapes of energy to control matter with unprecedented precision.

Optical Lattices, ahead of time?

The versatility of atomic trapping by lasers is because of the freedom in the functional form of lattice that can be generated by interference of monochromatic or polychromatic lasers, incorporating time dependence, control of relative phase, alteration in the parameters of the cavity (in case of standing waves), variation of polarization and several other strategies. According to the type of experiment, one may choose the trapping laser to be resonant, detuned or far detuned from characteristic frequencies of the subsystems (the atoms); one may need to choose specific wavelengths (as in optical lattice clocks) to make specific transitions independent of the intensity of trapping laser, or even consider higher multipolar effects. Even lattices that don't or rather can't exist in nature, which could only be enjoyed in theory, can be experimentally investigated with the emergence of this technology. For example, different kinds of atoms can be trapped in a 'designer' lattice to obtain a quasi-crystal, which is highly promising in realizing novel topological phases, superconducting systems, observing Anderson localization and so on. From simulating Kitaev chain and Majorana Zero Modes to simulating twistronics and valleytronics; Optical Lattices indeed have endless possibilities in quantum simulation. Szpak and Schützhold (2012) proposed an experiment to simulate Schwinger effect in a bichromatic optical lattice resembling the Hubbard model. They suggested that this can also provide insights on the non-perturbative nature of such atom traps. They assumed a 1D lattice of the form $V(x) = V_0 \sin^2(2kx) + \Delta V \sin^2(kx)$ and introduced the potential Φ as a deformation (remember, no magnetic field in 1D). Tuning the optical lattice such that $\omega_{osc} >> J >> M >> T$ (representing orders of energy associated), where ω_{osc} is the local oscillator frequency, J is the hopping potential, M is the mass and T is the effective energy; ensures the applicability of the single band Fermi-Hubbard model, validity of the continuum limit, the condition for Schwinger effect to occur and removing thermal excitations, nonetheless. The procedure is first starting with $\Delta V > V_0$, such that all atoms occupy the lower wells and remain there as ΔV is swept adiabatically until $\Delta V << V_0$. When the upper and lower wells are close enough, the deformation is introduced to complement the tunnelling from lower wells to upper wells. Now, if the lower wells be analogous to the Dirac sea, this procedure results into a particle-antiparticle creation, where the absence of an atom in the lower well can be considered like a 'hole' or the antiparticle. In 2014, Celi et al. proposed using atoms with M states trapped in a 1D optical lattice to have an effective 2D structure, where the extra dimension is the synthetic dimension arising from the internal states, i.e. each Zeeman level can be thought like a lattice point in this. This gives us the freedom to even go beyond the 3 + 1 dimensions. Emergent high-rank gauge fields due to higher dimensional symmetries can create exotic phases like Fractal Hofstadter Butterfly. We may be able to achieve an effective non-Euclidean manifold in the presence of higher dimensions. One of the most widely aspirational applications of Optical Lattices is in Quantum Computation. Due to the 3D mobility of these lattices, they simplify the quantum gate operations and the architecture of Cold-Atom-based qubits to a great extent. The optical lattice can be chosen far detuned from the resonant frequency of the qubits. As suggested by Brennen et al. (1998), controlled-NOT gate can be realized with higher fidelity by making pairs of atoms occupy same well by varying the polarization of the trapping lasers and then inducing a near resonant electric dipole by a secondary laser. This procedure significantly decreases unintended interactions. A proposal for realizing the famous Toric code, which could also be a ground for detecting Anyons, followed in Aguado et al. (2008). Anyons, as the name suggests, are particles with fractional or 'any' statistics; unlike Fermions or Bosons, they gather a complex phase on braiding around each other. The paper highlighted the ease of emulating an arbitrary lattice and the respective vertex and plaquette operators using lasers, which can be a generalized method to exhibit even more complex models, where non-Abelian or rather composite Anyons can also be found. Non-Abelian Anyons and essentially their controllability can lead to successfully achieve topological quantum computing, which is inherently robust and universal. Thus, Optical Lattices stand as one of the most promising hardware, if not better, for topological quantum computation in practicality. Optical lattices have facilitated the controllability of new degrees of freedom, certainly making it a touchstone for Condensed Matter Physicists. Nevertheless, it has found revolutionary use in other fields of Physics. Optical lattices have been among the most promising proposals for precise gravimetry and gravitational wave detection. In a scheme developed by Kolkowitz et al. (2016), the comparison of two mode-locked optical clocks set in far-apart satellites can help us probe Gravitational waves of frequencies as low as 10 mHz, incredibly more sensitive than LIGO.

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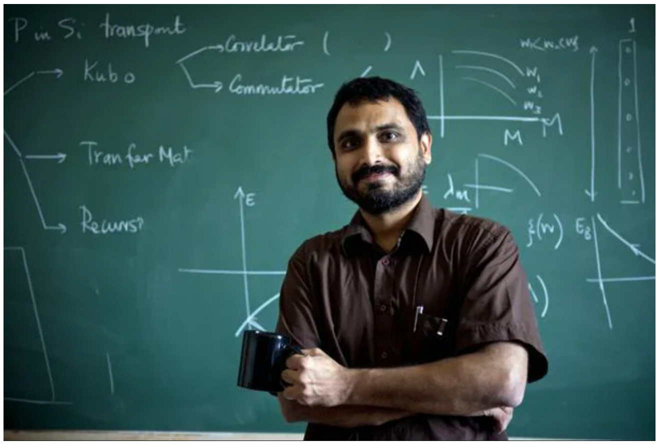
Phases of Matter and Physical Order : In Conversation with Prof. Vijay Shenoy

Susmit Roy, Panchariya Chinmay Anil

Prof. Vijay B. Shenoy is a leading theoretical physicist at the Indian Institute of Science, Bengaluru, known for his work in condensed matter physics, spanning interacting fermionic systems, topological phases of matter, and strongly correlated phenomena. In this interview, he reflects on his scientific journey, research philosophy, and broader perspectives on theoretical physics.



Prof. Vijay Balakrishna Shenoy

So, to begin with, what are your current primary research interests in condensed matter physics and can you please tell more about it.

So, I will tell you a little bit about what condensed matter physics as I see it and then tell you what are the things that we are exploring.

Broadly speaking, the best way to start seeing what condensed matter physics is, is to ask yourself what is it that you cannot live without today. If you ask that to any common person, they will say it is their mobile phone. If you ask what is it that makes the technology of mobile phones possible and think a little deeper, you realize that it is the ability to control electrons flowing through things. This is what is behind every mobile device or any device that we are using. It is a result of fundamental physics, with research undertaken in the 1920s leading to this. So what is it that we are using about electrons and quantum physics in these devices? You realize that electrons, when you put many of them together, form distinct phases. Just like atoms form liquid, gas, and solid phases, electrons also form phases. When electrons form a solid, that is what we call a band insulator. Band insulators are very important for mobile devices. You start with a band insulator, dope it, and then you get semiconductors. Metals are the fluid phase of electrons. Because of quantum physics, you also get interesting phases like magnets. Magnetism arises from electrons in atoms.

Much of these ideas of the phases of electrons were believed to be solved by the 1980s. Starting from Bloch physics, people developed the theory for about 50 years, and by then it was thought that everything was reasonably well understood, including superconductivity. Then came the discovery of the quantum Hall effect. The quantum Hall effect turned the field upside down. You got insulators in places where you never expected. It is a beautiful phenomenon from both basic physics and technology perspectives. Today, the resistance standard is based on the quantum Hall effect. Fundamental constants like Planck's constant and the charge of the electron are best measured using experiments like the Josephson effect and the quantum Hall effect. This was the background of condensed matter physics until around 2000. Around that time, people started asking whether quantum Hall–like phenomena could exist in higher dimensions. This led to the broader question: what are all the possible phases of electrons? By around 2015, at least for non-interacting electrons, it became clear how to classify these phases. Around the same time, quantum technology and synthetic quantum systems started to take off. Modern condensed matter experiments and quantum computing platforms involve many interacting qubits, with Josephson-junction-based–based technologies currently in the lead.

This raises the question: given a collection of interacting qubits, what phases can they realise? In this context, the fractional quantum Hall effect, discovered earlier, led to the notion of topologically ordered phases. Topological order is more exotic than topological insulators. It became clear that to classify distinct phases of interacting systems, the central idea is entanglement. Different patterns of entanglement classify different phases of matter.

One ongoing effort is to classify all possible phases arising from interacting degrees of freedom. In this process, a class of phases called fracton phases was discovered, which do not fit into the usual classification. One area we work on is fracton phases. To understand their broader interest, consider the problem of building good logical qubits from bad physical qubits. Qubits lose information over time, so the question is how to combine many qubits to form a stable logical qubit. The idea is to use properties of phases with protected ground-state degeneracy, protected not by symmetry but by topology. This is where topological order comes in. In systems with topological order, degeneracy arises from entanglement patterns. A famous example is Kitaev's toric code, which has been realized experimentally. The logical qubit is encoded in the degenerate ground-state manifold of many interacting qubits and is robust against local disturbances. However, at finite temperatures, this topological order melts due to the entropy gained by mobile defects. This motivates the question of whether one can design systems where excitations cannot move, not due to energetic constraints but due to the structure of the theory. Such models were discovered around 2014–2015 and are described by tensor gauge theories. In these theories, conservation laws are stronger. For example, if the dipole moment is conserved, isolated charges become immobile. These immobile excitations are fractons.

Our early work proposed a framework for studying such fractonic gauge theories by generalizing Maxwell electrodynamics to higher-rank gauge fields. These theories describe immobile point excitations, line-like excitations, and other structures. Around the same time, it was proposed that two-dimensional fracton theories are dual to elasticity theory. We explored this idea and showed that paper folding provides a classical realization of fractonic behavior. The inability to move a fold tip freely corresponds to fracton immobility. This work was done by **Nandagopal Manoj** during his undergraduate thesis. More recently, one of our PhD students, **Bhandaru Phani Parashar**, studied fractonic theories in two dimensions and asked whether fractons can form fractional Hall–like states. We found exotic properties, including unusual boundary excitations.

The second area that we have been thinking about is the following. So as I mentioned, there is a lot of effort in trying to create quantum systems starting from some, you know, elementary units like qubits, put them together and make them interact and so on.

So now if you think about the way people are approaching this is that they are very much inspired by phases that occur in condensed matter physics. We usually arrange degrees of freedom in some space, where they interact, and the low-energy description is a quantum field theory defined on a manifold like space, a wire, or a surface.

Around the time COVID started, we asked why we should be bound to manifold arenas if we can engineer qubits in any way we like. So we started exploring qubit models in non-manifold arenas. If you think of qubits as points and interactions as links, this naturally leads to graphs. Nandagopal and I started building models inspired by tree-like structures, graphs without loops, which we call arboreal models.

What we found was interesting from a basic physics perspective. If you take Kitaev's toric code, which can be used as a quantum memory but is unstable at finite temperature, and place it on an arboreal structure, it becomes fractonic. This suggests the possibility of stable quantum memory, at least conceptually. We also classified topologically ordered phases in such arboreal arenas.

Following this, with an undergraduate student, **Gurkirat Singh**, we studied fermion models on arboreal arenas and found phenomena very different from those on manifolds. On manifolds, a transition between a topological phase like a Chern insulator and a trivial insulator occurs at a single quantum critical point, requiring a gapless state where entanglement is restructured. In arboreal arenas, this restructuring does not happen at a single point. Subsystems hold on to their entanglement until parameters change further, so the quantum critical point gets extended into a region. The usual notion of scale invariance and simple phase transitions breaks down on non-manifold arenas. We are exploring what possibilities this offers. One striking result is that even when the bulk is gapless, protected edge states can exist, which is unusual since protected edge states usually require a gapped bulk. How broadly these phenomena apply is something we are continuing to investigate.

Most recently, we have decided to look at the relationship between artificial intelligence, machine learning, and physics. This is not a new idea. The inspiration comes from what happens at critical points, where the system seems to forget everything and only sees certain broad features of what is at the UV level. This is very similar to what happens in a classifier network. If you feed the network a picture of a dog, even with many deformations, it still recognizes the dogness, or canineness, of the dog.

The question is how the network sees this, and whether we can make this concrete in a calculation or a theory that shows a connection to the renormalization group. My belief is that the renormalization group flow itself can be cast as something like a network. As the length scale increases, the RG flow, or what is called the S-parameter renormalization flow, can be thought of as the depth of a network that classifies different points. The question then is whether we can push more concreteness into this idea. My colleague **Hiranmay Das** is exploring this within specific models.

These are some of the directions we are exploring.

As you mentioned, since the emergence of the quantum Hall effect, topology has played an important role in condensed matter physics. What are the different ways in which topological ideas arise in condensed matter systems, and what is the current understanding of topology in condensed matter physics?

That is a very broad question. When people say "topological," it can mean many different things, depending on context.

The simplest example of topology appears in band insulators with non-interacting fermions. In a band insulator, one has Bloch states forming conduction and valence bands, each characterized by a crystal momentum in the Brillouin zone. What one does is to fill the valence band.

One way of thinking about topology, particularly in the context of topological insulators, is to view the Bloch states in the valence band as objects in some space. For each point in the Brillouin zone, the valence-band state corresponds to a point in another space.

Consider a one-dimensional insulator. Its Brillouin zone runs from $-\pi$ to π, with $-\pi$ identified with π, so it has the topology of a circle. Each Bloch state carries an intrinsic phase, which can be visualized as the hand of a clock. As one goes around the Brillouin zone, this phase may wind around the clock zero times, once, or multiple times. These windings cannot be undone without a drastic restructuring and distinguish different insulating phases. This is one sense in which topology arises in condensed matter physics.

Another way topology appears is in the quantum Hall effect. One can describe it using band topology, where the winding is characterized by the Chern number. However, there is a deeper sense of topology in this case. One can ask how to describe the phase without explicitly referring to electrons. By coupling the electrons to light and integrating out the gapped electronic degrees of freedom, one obtains an effective theory for the electromagnetic field. This effective theory is a Chern-Simons theory.

The Chern-Simons theory is topological in a different sense. It is a topological quantum field theory whose properties depend only on the topology of the manifold on which it is defined, and not on its geometry. Metric properties such as distances do not enter the theory. For example, the theory defined on a torus is the same regardless of how the torus is stretched or deformed. When one speaks of topological order, this is the sense of topology that is meant: ground-state degeneracy determined solely by the topology of the underlying manifold.

There is yet another way in which topology enters condensed matter physics, through defects in symmetry-broken phases. Some defects are constrained by topology. A classic example is vortices in superfluids. Creating an isolated vortex requires significant effort, and once created, it remains stable for long times due to topological constraints.

Thus, the word "topological" must be understood contextually, as it carries different meanings in different settings.

In terms of current directions, one major area of exploration is band topology and how it can be used in a practical way, for example by switching between topological phases using external fields to design new devices. Another important direction concerns topological order in the sense of Chern-Simons theory, where one asks whether such phases can be used for quantum memories and topologically protected quantum computation. In these systems, information stored in topological excitations is robust against local perturbations.

These are the main ways topology appears in condensed matter physics and the directions people are exploring today.

One of your highly cited works involves the theoretical prediction of the 'Rashbon' Bose-Einstein condensate. Could you explain to us what exactly a Rashbon is and take us back to the moment of that insight?

This line of work was initiated some time ago, and I should begin by noting that I am no longer actively working on these problems; they belong to an earlier phase of my research. The broader question that motivated this area, however, remains central to condensed matter physics: how can one realize superconductivity under ambient conditions?

To address this, one must understand what controls the superconducting transition temperature. There is no universal answer, as the transition temperature depends sensitively on microscopic details. A natural question is whether making the attractive interaction between electrons very strong could enhance the transition temperature. Intuitively, if electrons form tightly bound pairs, one might expect them to remain paired even at higher temperatures.

However, something nontrivial happens in this limit. When the attractive interaction becomes very strong, two spin-1/2 electrons bind into a singlet, which is a bosonic object. The system then crosses over from a BCS superconductor to a Bose–Einstein condensate of tightly bound pairs. In this regime, the transition temperature is no longer controlled by pairing, but by the condensation temperature of these composite bosons.

Around 2010, largely motivated by advances in synthetic quantum systems, particularly cold-atom platforms, there was renewed interest in the BCS–BEC crossover, which interpolates between weak and strong attractive interactions. At the same time, researchers began exploring whether effective gauge fields could be engineered in such systems. Gauge fields couple to the motion of particles and can be thought of as generalizations of vector potentials, and cold-atom experiments provided a way to realize such couplings in a highly controllable manner.

These developments went beyond conventional Abelian gauge fields. It became possible to engineer non-Abelian gauge fields, where the internal degrees of freedom of fermions, such as spin, are actively mixed as particles move through space. In condensed matter language, this corresponds to spin–orbit coupling.

In work with **Jayanth Vyasanath**, who was then a PhD student here and the primary driver of this project, we investigated what happens when the strength of spin–orbit coupling is increased. We found that when spin–orbit coupling becomes the dominant energy scale, any attractive interaction, no matter how weak, leads to the formation of tightly bound states. These bound states arise due to Rashba-type spin–orbit coupling and are therefore referred to as Rashbon states.

This phenomenon is best understood from a renormalization-group perspective. A weak attractive interaction becomes a relevant perturbation and flows toward a Rashbon fixed point. The key outcome is that strong pairing can emerge without requiring intrinsically strong attractive interactions.

From the standpoint of material design, this suggests a possible guideline. If one can engineer systems where the fermionic energy scale, set for example by the density, is smaller than the spin–orbit coupling scale, pairing tendencies can be significantly enhanced. While realizing such conditions in real materials is extremely challenging, this framework provides a conceptual direction for exploring routes toward higher-temperature superconductivity.

That is the essential idea behind this body of work.

Theoretical physics is vastly interconnected, in the sense that seemingly unrelated phenomena seem to have deep connections. What is your opinion on the interplay of concepts between seemingly distinct fields?

Yes, that is really the operative idea behind the question. This is, in fact, what excites me most about physics and what continues to motivate me.

What is remarkable is that phenomena which initially appear completely unrelated often turn out, upon deeper examination, to be intimately connected. This realization begins with very elementary examples. For instance, if one takes something as simple as a single qubit and studies its thermodynamics, it can map onto a classical statistical model in one higher dimension. From there, one naturally encounters ideas such as dualities and a web of unexpected connections across seemingly disparate systems.

The deeper question, then, is how it is possible that very different physical phenomena are governed by the same underlying structures. One could, of course, take this in a philosophical direction and ask why nature organizes itself in this way. I generally avoid that route, because posing such questions meaningfully requires a great deal of experience. One needs to have worked through many concrete examples, many dualities, and many explicit realizations before one can even begin to see the organizing principles at work.

What does emerge, however, is the understanding that there exists an overarching set of ideas that transcends individual models or systems. These ideas manifest themselves in different ways across different physical settings, but the underlying structure remains the same. Many apparently distinct systems are simply different realizations of the same fundamental principles.

So I am not entirely sure whether I have directly answered your question, or whether you were simply inviting a broader reflection. But this is precisely what I find most compelling about physics: the fact that a single theoretical framework can unify and describe phenomena that, on the surface, appear entirely unrelated.

As you mentioned while discussing condensed matter physics, the discovery of the quantum Hall effect and later the fractional quantum Hall effect led to many important developments. What is the current state of the field today, particularly in condensed matter physics and statistical mechanics, and what are some of the major directions or discoveries underway?

One of the directions I mentioned earlier concerned the classification of phases of matter. Traditionally, this entire framework has been developed within equilibrium physics.

Today, however, condensed matter physics has evolved significantly and is strongly influenced by developments in quantum information theory and quantum technology. The kinds of questions we ask are increasingly shaped by what is experimentally possible on modern quantum platforms. Advances in quantum computing, quantum simulation, and measurement techniques are now actively driving new directions in the field.

A good example of this is the recent work on what are known as measurement-induced phase transitions. Consider a quantum system subjected to a protocol in which it evolves unitarily for some time, is then measured, allowed to evolve again, measured again, and so on. Remarkably, by tuning the rate or strength of these measurements, one finds that the long-time state of the system can exhibit qualitatively different patterns of quantum correlations.

What is particularly striking is that this behavior exhibits features analogous to critical phenomena. There exists a critical measurement rate or measurement strength at which the system realizes a scale-invariant, critical state. These phenomena were first discovered through numerical studies, where researchers analyzed the entanglement structure of states generated by such measurement-and-evolution protocols.

Despite the system being intrinsically non-equilibrium, one can draw a phase diagram as a function of measurement rate or strength, and identify sharp transitions between distinct phases. This naturally raises the question of why such transitions are important.

One immediate motivation is state preparation. If one wants to engineer a quantum system into a particular target state, understanding these measurement-induced transitions can provide powerful protocols for doing so. From a more conceptual perspective, this opens up an entirely new version of the classification problem. Earlier, the question was what phases are possible for systems governed purely by a Hamiltonian. Now, one can ask what phases and phase transitions arise when measurement dynamics are an essential part of the evolution.

This also allows for further generalizations. For instance, one can ask how these measurement-induced transitions behave on non-manifold structures such as arboreal graphs, or how they interact with other exotic settings. These possibilities create a large and active landscape of open questions.

Let me also mention some complementary directions that are more closely tied to materials science. One major motivation, again driven by technological considerations, is the long-standing question of whether superconductivity can be realized under ambient conditions.

The discovery of graphene in the early 2000s was a major breakthrough, eventually leading to a Nobel Prize, and it opened the door to many new ideas. One such idea involved stacking layers of graphene with a slight relative twist, producing a Moiré pattern. Around 2016 to 2018, experiments revealed that such twisted bilayer graphene systems host a variety of striking quantum phases of electrons.

Although the temperatures at which these phases appear are not particularly high, the richness of the observed phenomena is remarkable. These systems provide a powerful platform for engineering strongly correlated electronic phases through precise control of geometry rather than chemical composition.

This has become a very active direction in condensed matter physics, where researchers aim to engineer novel quantum phases not only in synthetic quantum systems but also in real materials by cleverly arranging and structuring them. Together, these developments illustrate some of the key directions the field is currently exploring.

With the rise of data driven science, what are your views of the role of AI and ML in physics and research in general?

The honest answer is that I have not really had the opportunity to think deeply about these issues. Perhaps not very wisely, but due to a lack of time and overcommitment to many different things, I have not incorporated AI into my own research, nor do I use AI tools very much.

I think it is useful to ask what role AI can play in research more broadly. One obvious possibility is that AI could help us address well-defined problems where we are unable to find an answer. One could ask an AI system for a possible answer or direction, and then critically examine whether that answer makes sense. In that sense, AI can certainly be helpful.

However, in condensed matter physics, progress is often not about answering a clearly posed question. There is a significant creative component, where the key step is formulating the right question in the first place. For example, the discovery of fracton phases emerged because someone asked whether it was possible to design systems with fundamentally immobile excitations. It is not clear to me whether current AI systems are capable of contributing meaningfully to that kind of creative leap. Perhaps generative AI might help in some way, but my understanding is not deep enough to say this with confidence. I also do not have a clear sense of where efforts toward artificial general intelligence currently stand. I do not know whether present-day systems have reached that level, or how close they are. From my limited exposure, AI sometimes produces remarkably insightful responses and at other times gives answers that are clearly off the mark. This variability makes it difficult for me to assess its true capabilities.

What genuinely fascinates me, though, is how AI works at a fundamental level. Rather than using it as a tool, I am more intrigued by the question of what these systems are actually learning. Even setting aside generative models, one can ask what a classifier network learns, how it encodes information, and whether we can develop a theoretical understanding of that process. This naturally connects to questions I care about, such as whether ideas from renormalization group theory can be brought to bear on neural networks. I should also say something about the use of AI at early stages of one's career. Regardless of whether AI tools are used or not, it is crucial to develop the ability to think independently. When faced with a question, whether self-generated or posed by someone else, one needs the skills to engage with it meaningfully without relying on external prompts. In that sense, you yourself must be the source of the stimulus.

Whether AI can later serve as a complementary tool is an open question. My intuition is that it may be more effective to first struggle with a problem independently, make some progress, and only then use AI tools. At that stage, the responses provided by an AI system are more likely to be interpretable and useful, rather than confusing or misleading. To be clear, I am strongly in favor of new directions and new tools. If AI turns out to be genuinely useful, we should absolutely use it. My hesitation does not come from opposition, but from uncertainty. I do not yet have a good sense of where the field is heading or what AI systems will be capable of even a couple of years from now. Given how rapidly things are evolving, it seems entirely possible that these are still very early days, and that much more clarity will emerge with time.

Looking back at your academic trajectory, what were some of the most significant pivots or defining moments? Your career path is unique in that it marked a significant transition between two different research cultures: Mechanical Engineering and Physics. What were the significant moments that drove this change? And practically speaking, how easy or difficult was it to navigate through this transition?

What motivated me is actually a slightly subtle question. To be honest, I did not really need an external motivation. From childhood, I was deeply interested in physics. However, after my 12th standard, I had to make certain practical decisions, and given the options available to me at that time, I chose to pursue engineering.

I went on to do a PhD in engineering as well, but there were a couple of defining moments along the way. After my undergraduate studies, I became increasingly interested in the mathematical aspects of physical problems. I was looking for areas where mathematical ways of thinking could be applied in a meaningful way, and that search eventually led me to Brown University for my PhD.

While I was there, I encountered an atomic force microscope for the first time. Seeing an AFM was a transformative experience. It made the atomic world feel tangible in a way it had not before. I suddenly realized that atoms are not just abstract entities in equations; they are real objects that one can probe and manipulate. That experience shifted my perspective and made me appreciate the importance of connecting mathematical ideas with physical reality.

After that, I more or less followed the natural trajectory of my career, responding to opportunities as they arose. I joined IIT Kanpur, and later moved to Bangalore to join the Materials Research Centre at IISc.

Another important turning point came when I started hearing talks on high-temperature superconductivity. While visiting various institutes in India, I attended a talk that emphasized how many puzzling and unresolved phenomena existed in this field. That intrigued me, and I began reading about it. This was the early 2000s, when internet access was just becoming widespread, and it suddenly became much easier to explore unfamiliar topics and follow threads of curiosity.

Around that time, I began interacting with colleagues in the physics department, often through informal conversations at the faculty club. I would casually ask what was happening in the field, and those discussions drew me in further. I attended talks, including one by H. R. Krishnamurthy on band dynamics, and that deepened my interest. Eventually, these interactions led to collaborations and a more sustained engagement with condensed matter physics.

Looking back, I am not sure there was a sharp transition at all. It feels more like a crossover. I simply followed what I found interesting, without consciously planning a shift. My research interests evolved naturally, without any deliberate effort to force a change.

There were, of course, practical transitions in day-to-day life, such as moving from one department to another. In that respect, I was fortunate to receive a great deal of support from the institute and from senior colleagues, including H. R. Krishnamurthy, Chandran, Ajay Sood, T. V. Ramakrishnan, and many others. Their openness and encouragement made the move into the physics department smooth and welcoming.

But in terms of intellectual motivation, there was no abrupt change. My interests simply grew and evolved organically, guided by curiosity rather than by any predefined plan.

What is your most crucial piece of general advice for undergraduate students today who are passionate about condensed matter physics?

The first thing I would emphasize is that it is very important to see things in a broader perspective. So let me slightly reframe your question. I would not advise anyone to pursue condensed matter physics or high-energy physics as such. That is not the right way to think about it. What I would suggest instead is to find a question that genuinely excites you. That question might come from what is conventionally called condensed matter physics, or from high-energy physics, or from somewhere else entirely.

The key point is that you should not worry too early about labels. At an early stage, you should avoid saying, "this is condensed matter" and "this is high energy." Instead, you should try to look for unity in ideas. This connects back to your earlier question about finding common structures across seemingly different phenomena.

From the perspective of an undergraduate, I think one of the most important things is to have a good peer group. When you enter an undergraduate program, it is perfectly fine not to be sure about what you want to specialize in. In fact, that uncertainty can be a good thing because it means you are open to new ideas. On the other hand, some people know very early on, even by middle school, that they want to study physics. In either case, it is crucial to find peers with whom you can exchange ideas, discuss concepts, and explore questions together.

In this context, I want to emphasize something important. Very often, especially at the undergraduate stage, a lot of emphasis is placed on knowing many things. Knowledge is certainly important, and I am not dismissing that at all. But what matters even more is asking yourself a simple question: with what I know, what new have I done? This question has nothing to do with whether you choose physics, anthropology, or any other field. It is a way of thinking that applies universally.

If you want to pursue science, research, or any intellectually driven path, you must constantly ask yourself this question. With the things I have learned, what new insight have I generated? What new connection have I made? If I were to go back to my undergraduate years with what I know now, I would spend much more time talking to a wide range of people, trying to understand what the frontiers are, what questions remain puzzling, and what problems are still open. Over time, you develop a sense of taste. Certain problems begin to resonate with you more than others, and those are the ones you should pursue, ideally in collaboration with peers, through discussion and shared exploration.

This may sound idealistic, and in practice it will always be tempered by constraints and practical considerations. But having an ideal is important. Without it, there is nothing to guide how you adjust to those practical realities. That is the kind of mindset I would encourage in undergraduates.

It does not really matter what you call the field. You can call it condensed matter physics or something else entirely. The label is secondary. What matters is whether the problem excites you and whether you feel compelled to explore it. You should remain open to discussion and actively seek commonality between different ideas. Making connections is important, but even more important is using those connections to push boundaries and open up new directions.

If I had to summarize this succinctly, especially in the context of undergraduate education in India, there is a strong emphasis on learning and acquiring knowledge. That emphasis is necessary and valuable. But what I have observed over the years is that much less emphasis is placed on creativity. Students should be encouraged to ask themselves, every time they learn something new, what they can add to it. How can they view it differently? Can they combine it with something else to create a new idea?

If you cultivate this habit of constantly asking what you can do with what you know, you will find that your intellectual life becomes much more engaging. You will be excited more often, because you are actively creating rather than passively absorbing. That, in essence, is what I wanted to convey.

Spontaneity of Symmetry Breaking

Arpit Chhabra, Aaradhya Sachin Kulkarni

In this article, we will explore how various systems in the universe undergo the recurring mechanism of spontaneous symmetry breaking. From superconductors, to ferromagnets, fundamental particles (surprisingly, even classical systems!), and general relativity, everything is rife with phase transitions that spontaneously break symmetry. Starting from one classical and one quantum mechanical example, we will build the way to finally understand how the Higgs boson "provides mass" to particles through the Anderson-Higgs mechanism.

Introduction

Here's a fun and intuitive thought experiment: Imagine an extremely awkward dinner with your distant relatives. There are people sitting on a round table with their plates, and between each of the two plates is a glass of water. Now, the problem is, everybody is thirsty, but nobody wants to reach for their glass because they are unsure whether theirs is the one on the left, or the right. So far, everything is perfectly symmetric, until one of the relatives randomly decides to choose the glass on their right side. Now suddenly everybody wants to quench their thirst, and they all reach for the glass to their right. What was previously a symmetric setup is now no longer as symmetric (the awkwardness persists). This is one of the simplest analogies of spontaneous symmetry breaking, a phenomenon which is very rich and abundant in nature. In modern condensed matter physics, there is a concept of universality: even though some physical systems may look vastly different at face value, their underlying theories are more or less similar in structure to each other. Hence, solving one problem allows us to exactly map the solution to the other (yet unsolved) systems! We can see such a similar notion of universality in spontaneous symmetry breaking, in its sheer vastness of occurrence. More rigorously, spontaneous symmetry breaking can be seen as a mathematical feature of the potential in the system, which is a function of some parameter such as magnetization, temperature, time, etc. When this potential admits multiple stable points after some critical value of the parameter, the system decides to randomly settle into one of these stable solutions. In short, Spontaneous Symmetry Breaking occurs when the underlying laws of motion (the Lagrangian/Hamiltonian) possess a symmetry, but the lowest energy state (the Vacuum/Ground state) does not.

Structure of the article

The structure of the article is as follows: 1) A classical example of a bead on a ring rotating about the Z axis. 2) A quantum mechanical example from superconductivity, along with a very interesting caveat. 3) The Anderson-Higgs Mechanism.

Basics

Taking a step back, we go through some basic ideas for people who are not familiar with some terminology that is used further. Symmetry is something we all have an intuition about, or rather an ambiguous idea about. The idea usually goes that symmetry is the invariance of the system, but exactly what do we mean by this statement? To say something substantial, we will have to start with a baseline of understanding, which in this case is "Lagrangian". If you haven't encountered Lagrangian before, you can think of it as a $\frac{1}{2}mv^2 - V(x)$, which is basically kinetic energy minus potential energy. But this turns out to be a powerful quantity as it contains almost all the information about our system. This allows us to introduce the Action S:

$$S = \int_{t_i}^{t_f} \mathcal{L}(t)\, dt \tag{80}$$

Now coming back to invariance: a symmetry we mean here is any transformation of the field or coordinate that keeps our action invariant will be named a classical symmetry. To give an example from what we already know, with the example of a bead:

$$L = \frac{1}{2}mR^2\dot{\theta}^2 - mgR\cos\theta + \frac{1}{2}m\dot{\phi}^2R^2\sin^2\theta \tag{81}$$

Furthermore, for now we can think of Hamiltonian as Total energy, i.e., for the case of non-relativistic cases

$$H = \frac{1}{2}mv^2 + V(x)$$

The Classical example - Bead on a ring

Consider a simple physical system we all have seen before, a bead on a ring. We will assume that the ring is massless, placed vertically, and is rotating around the Z axis.

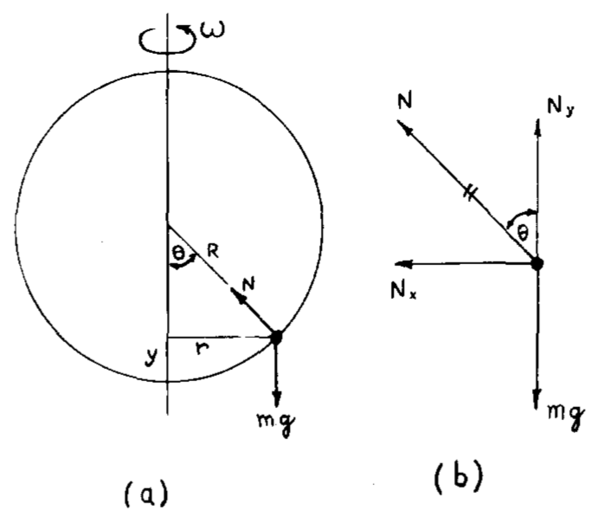


Figure 13: Bead on a rotating circular rod. The frictionless rod is rotating about a vertical diameter at constant angular frequency ω. (a) When the bead remains at constant θ, the only two forces acting on it are the normal force N and gravity. (b) Resolution of the normal force into horizontal and vertical components.

Now, we can write the Lagrangian of the system, defined as $L = T - V$:

$$L = \frac{1}{2}mR^2\dot{\theta}^2 - mgRcos\theta + \frac{1}{2}m\omega^2R^2sin^2\theta \tag{82}$$

The constraint that the bead is fixed on the ring has been taken care of. We can write the potential energy $V(\theta)$ as:

$$V(\theta) = mgRcos\theta - 0.5m\omega^2R^2sin^2\theta \tag{83}$$

We can do something interesting now: we wish to compute the minima of this potential. This is easily done by $V'(\theta) = 0$:

$$sin\theta(g + \omega^2Rcos\theta) = 0 \tag{84}$$

This is solved to obtain the extrema $\theta = 0$ and $\theta = \pi$ (corresponding to the top and bottom of the ring), and an interesting solution $cos\theta_0 = -\frac{g}{\omega^2R}$. Since $cos\theta$ is bounded, we have the condition for this solution as $\omega \geq \omega_c$, where $\omega_c = \sqrt{\frac{g}{R}}$. It can be easily checked using the sign of $V''(\theta)$, that this θ_0 is the new stable equilibrium point. Thus, we have found a new equilibrium position that only exists when the frequency is above some critical value! This is a hallmark of spontaneous symmetry breaking. Notice how $cos\theta$ is an even function of θ, and hence θ and $-\theta$ are both equally likely solutions. (The Lagrangian has this symmetry too, and as we have noted before, the bead settling randomly into either one of the positions will break this "inversion" symmetry we had!)

The quantum mechanical example and a subtle point

The Example

Now that we have seen how symmetry breaks spontaneously in classical systems, we will look at how this happens for quantum mechanical systems[1] - hopefully, all will go seamlessly. To begin with, we consider the case of a classical field with the Lagrangian

$$\mathcal{L} = \frac{1}{2}\dot{\phi}^2 - \frac{1}{2}m^2\phi^2 - \frac{\lambda}{4}\phi^4 \tag{85}$$

We see that the potential has a $\mathbb{Z}_2$ symmetry, $\phi \to -\phi$.

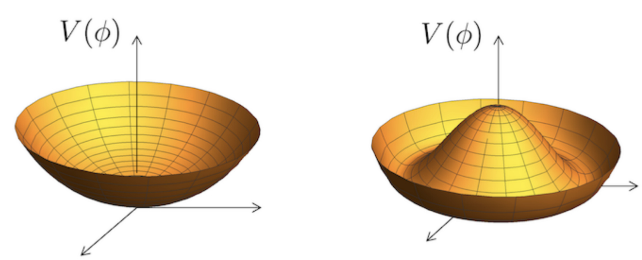


Figure 14: On the left: the potential with $m^2 > 0$. On the right, the Mexican hat potential with $m^2 < 0$.

If $\lambda > 0$ and $m^2 > 0$, we have only one minimum at $\phi = 0$. But if $m^2 < 0$, we will have two possible minima: $\phi = \pm x = \pm\sqrt{\frac{-m^2}{\lambda}}$, and now ϕ is not invariant under the $\mathbb{Z}_2$ symmetry. Expanding the potential around one of these ground states ($\phi = x + \sigma$) gives us[2]:

$$V = \lambda(x^2\sigma^2 + x\sigma^3 + \frac{1}{4}\sigma^4), \tag{86}$$

[1] Still, we will mainly talk about classical field theory as there are further subtleties when going to quantum fields

[2] You can ask why we expanded only for $m^2 < 0$ and not for $m^2 > 0$, the basic idea being we didn't have 2 minima to expand around, we just had a single minima around $\phi = 0$ around this point expansion will retain $\mathbb{Z}_2$ symmetry

which is clearly invariant under the initial $\mathbb{Z}_2$ symmetry. Thus, our old symmetry has been broken here. We also take note of the fact that this potential here is a double-well-type potential. One might feel there is no motivation for this potential. Why should we worry about this? You have already seen this potential, which can be seen by going back to the example of a bead on ring:
The velocity of the bead on the rotating ring is

$$v_\varphi = r\omega = \omega R \sin\theta.$$

$$L = T - V = \frac{1}{2}mR^2\dot{\theta}^2 + \frac{1}{2}m\omega^2 R^2 \sin^2\theta - mgR(1-\cos\theta).$$

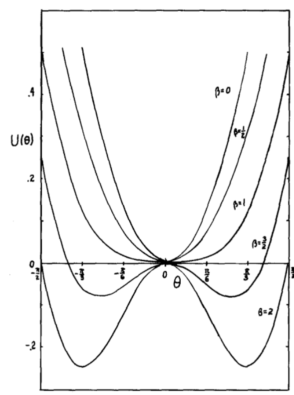


Figure 15: The dimensionless effective potential $U(\theta)$. The potential U is plotted as a function of θ, for various fixed values of β $(= \omega^2 R/g)$. Note that for $\beta > 1$, the potential becomes unstable at $\theta = 0$, and develops two minima at finite $\theta = \pm\theta_0$.

One can also express the Lagrangian in terms of an effective potential V_e:

$$L = \frac{1}{2}mR^2\dot{\theta}^2 - V_e,$$

$$V_e \equiv mgR\left[(1-\cos\theta) - \frac{1}{2}(\omega^2 R/g)\sin^2\theta\right].$$

Define the dimensionless potential

$$U \equiv \frac{V_e}{mgR} = (1-\cos\theta) - \frac{1}{2}\beta\sin^2\theta \tag{87}$$

$$= 2\sin^2\left(\frac{\theta}{2}\right)\left[1 - \beta\cos^2\left(\frac{\theta}{2}\right)\right], \qquad \beta = \frac{\omega^2 R}{g}. \tag{88}$$

Plotting $U(\theta)$ reveals the mechanism clearly (see Figure above). For low speeds ($\beta < 1$), the graph is a simple parabola with a single minimum at $\theta = 0$. However, once the speed exceeds the critical value ($\beta > 1$), the center becomes unstable (a local maximum), and two new deep minima appear at $\pm\theta_0$. This shape is mathematically identical to the 'Mexican Hat' potential used in field theory, identifying β as the control parameter analogous to the mass term m^2.

Subtle point

Here comes the mind-blowing part: If we try to consider the same situation in quantum mechanics, we observe something interesting: Since the central barrier in this double-well potential is finite, the states have a non-zero probability of tunneling into each other. This means that there will never truly be a singled out, symmetry broken state, as the two obtained states can tunnel across the barrier! One may try to remedy this problem by constructing localized states near the minima. But this does not work, as they will not remain eigenstates of the parity operator as well as the Hamiltonian. We can see that for a symmetry to exist in a quantum mechanical state, the corresponding unitary operator $U(g)$ must commute with H (and we will have $U|\psi\rangle = e^{i\theta}|\psi\rangle$.) Thus, as long as we are in an energy eigenstate, it is guaranteed that the energy eigenstate will remain invariant under this unitary up to a global phase, and thus will retain the symmetry. The death knell has rung for spontaneous symmetry breaking in quantum mechanics!

The example

One might wonder how other spontaneously broken symmetries exist, then: ferromagnets, superconductors, and the like. Aren't they quantum mechanical systems too? The very interesting answer to this is that despite them being quantum mechanical in nature, there is a very subtle fact about these systems: they host an enormous (or variable!) particle number. Ferromagnets have their rotational symmetry spontaneously broken in the thermodynamic limit, and superconductors, with their variable particle number, chooses a definite coherent phase, thus breaking the U(1) symmetry.

We will now begin to demonstrate how spontaneous symmetry breaking takes place in superconductors. We begin by noticing that the Bardeen-Cooper-Schrieffer (BCS) Hamiltonian, given by:

$$H = \sum_{k,\sigma}\xi_k c^\dagger_{k,\sigma}c_{k,\sigma} - \frac{g}{V}\sum_{k,k'} c^\dagger_{k\uparrow}c^\dagger_{-k\downarrow}c_{-k'\downarrow}c_{k'\uparrow} \tag{89}$$

where ξ_k is the single particle energy, g is a positive attractive interaction and V is the volume, commutes with the number operator $\hat{N} = \sum_{k,\sigma} c^\dagger_{k,\sigma}c_{k,\sigma}$. If this form is unfamiliar to you, don't worry about it. As the name suggests, the role of this quantity in the Hamiltonian is to give the total number of particles which is same as first quantity in Hamiltonian upto ξ_k. Since $\hat{N}$ and $\hat{\phi}$ are conjugate variables, the number operator acts like the generator of rotations given by $U(\phi) = e^{i\hat{N}\phi}$.

Thus, the BCS Hamiltonian is invariant under a U(1) transformation. This is also the symmetry that corresponds to charge conservation. We will now define the pairing operator B, which is the microscopic version of the superconducting order parameter:

$$B = \sum_k f_k c_{-k\downarrow} c_{k\uparrow} \tag{90}$$

We will digress a moment to define what the order parameter is. In the theory of phase transitions, one often expects a phase transition to occur when a symmetry is broken (slight caveat for the curious - look up topological phase transitions, they do not fit this paradigm.). A phase transition is often tracked by the value of a measurable called as the order parameter - a sudden change in its value means a phase transition has occurred, i.e a symmetry has broken. In the classical example, the angle θ is the order parameter, as it becomes nonzero after the transition. (Quick exercise: figure out what the order parameter in the next section is!) Now, B (the order parameter here) does not commute with the number operator $\hat{N}$, and transforms in the following manner under a U(1) transformation:

$$UBU^\dagger = e^{-2i\theta} B \tag{91}$$

Thus, a state that has a nonzero expectation value of B will break the U(1) symmetry.

Higgs Mechanism

We will start with a double-well potential again (hope you are not bored yet). We consider the Abelian Higgs model with action[3]

$$S = \int d^4x \left(-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + (D_\mu \phi)^\dagger (D^\mu \phi) - \frac{\lambda}{2} \left(|\phi|^2 - v^2 \right)^2 \right) \tag{93}$$

We expand around the classical vacuum $\langle \phi \rangle = v$ using

$$\phi(x) = (v + \sigma(x))\, e^{i\theta(x)}. \tag{94}$$

Here $\sigma(x)$ is the radial excitation and $\theta(x)$ is the angular mode. Why do we have the term $e^{i\theta(x)}$ in transformation of the potential? The reason is that this transformation keeps the action invariant, which we have to take into account. Doing exactly what we have done before, we can see our potential take a form

$$V(\phi) = \frac{\lambda}{2} \left((v+\sigma)^2 - v^2 \right)^2 = \frac{\lambda}{2} \left(2v\sigma + \sigma^2 \right)^2. \tag{95}$$

[3] where the covariant derivative is

$$D_\mu \phi = (\partial_\mu - ieA_\mu)\phi. \tag{92}$$

The quadratic term is

$$V(\sigma) \supset 2\lambda v^2 \sigma^2. \tag{96}$$

Thus, the mass of the Higgs excitation σ is

$$m_\sigma^2 = 2\lambda v^2. \tag{97}$$

Conclusion

In summary, a single pattern underlies the bead on a rotating ring, superconductors, and the Higgs sector of the Standard Model: a symmetric theory whose potential develops multiple degenerate minima, forcing the system to choose a less symmetric ground state. This simple mechanism explains why classical systems pick a direction, why superconductors acquire a phase, and how the Higgs field endows particles with mass through the Anderson–Higgs mechanism. These examples provide a common intuitive language for approaching more formal treatments of spontaneous symmetry breaking in field theory.

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Spacetime Atoms: Causal Set Theory

Ayushman Joshi

The Puzzle of Quantum Gravity

Arguably the most central problem facing fundamental physics today is the quest for a theory of quantum gravity. This is the search for a single theoretical framework that can unite its two great pillars: **General Relativity (GR)** and **Quantum Field Theory (QFT)**.

General Relativity (GR) is Einstein's masterpiece, our geometric picture of gravity. It tells us that gravity is not a "force" pulling things down, but rather the result of spacetime itself, this four-dimensional, continuous fabric, which bends and curves in response to matter and energy. It is the backbone of modern cosmology, explaining everything from planetary orbits to black holes and gravitational waves.

Quantum Field Theory (QFT) is the language of the microscopic world. It describes the other three fundamental forces (electromagnetism, the weak, and the strong force) and underpins the Standard Model of particle physics, which is our highly successful "parts list" of all known elementary particles and their interactions. In QFT, the fundamental building blocks are not particles, but all-pervading fields (like a magnetic field, but for every particle type), and the "particles" we see are just a "quantum"—a discrete packet—of energy in that field. It has produced some of the most precise predictions in all of science.

Individually, they are spectacularly successful. Together, they resist unification within a single, consistent framework.

GR is classical and deterministic, meaning that it describes a smooth, dynamic stage where, if you know the starting conditions, you can predict the future perfectly. QFT is probabilistic and quantum, describing particle actors on a fixed, flat stage where you can only predict the probability of an outcome. When we try to combine them—to apply quantum principles (like probability and discrete packets) to the stage of spacetime itself—the mathematics descends into conceptual and mathematical chaos.

The Tyranny of the Infinitesimal

The core of the conflict lies in the assumption of the **continuum**: the idea that spacetime is infinitely divisible. Think of it as a perfectly smooth line, which you can zoom into forever, and it always remains a line.

In quantum field theory, this assumption means that the fields can oscillate with arbitrarily short wavelengths (corresponding to arbitrarily high energies), leading to "ultraviolet" infinities in calculations. When physicists try to calculate a value, this "infinite divisibility" means they have to add up an infinite number of contributions, and the answer blows up to infinity. Physicists developed a powerful mathematical procedure called **renormalization** to tame these infinities. In essence, it's a way of absorbing the infinities into a few parameters that we can actually measure (like the mass and charge of an electron), effectively "sweeping the infinities under the rug" to get a finite, usable answer. It works beautifully for the Standard Model.

But when this same trick is applied to gravity, the math breaks down. Gravity is **non-renormalizable**. The infinities become uncontrollable; you get an infinite number of different types of infinities, and the perturbative approach loses predictive power.

General relativity, meanwhile, predicts its own breakdown. At the centers of black holes or the very beginning of the universe (the Big Bang), the theory predicts "singularities"—points of infinite density and curvature where the equations stop making sense (like dividing by zero). These are red flags from our own best theory of gravity, telling us that our continuum picture has reached its limit.

A Search in the Dark

Unlike past revolutions in physics, this one has almost no direct experimental guidance. The natural scale where quantum gravity effects should dominate is the **Planck scale**, an impossibly small realm where gravity and quantum effects are expected to become equally strong. The Planck length (l_P) is roughly 10^{-35} meters—about twenty orders of magnitude (a one with twenty zeros) smaller than a proton. The corresponding Planck energy (E_P) is around 10^{19} GeV (Giga-electron Volts, a unit of energy). For perspective, the Large Hadron Collider (LHC), our most powerful accelerator, can only reach energies of 10^4 GeV. We are many orders of magnitude too weak to probe this scale directly.

With no direct experiments to light the way, physicists must rely on mathematical consistency and conceptual clarity. This has led to a branching of creative, competing ideas—from **String Theory** (which posits everything is made of tiny vibrating strings in extra dimensions) and **Loop Quantum Gravity** (which suggests space itself is made of discrete, quantized loops) to this radical, minimalist alternative.

A New Proposal: Causal Set Theory

Causal Set Theory (CST) begins by treating the continuum as emergent rather than fundamental. Championed by physicist Rafael Sorkin, its proposal is as elegant as it is simple: the fundamental structure of the universe is not a continuous manifold (a smooth, curved shape), but a discrete collection of events ordered by causality.

In this view, the universe isn't built on "points in space" but on a network of relationships, which events can influence with others (see, for example, [1, 2, 3]). The slogan of CST sums it up neatly:

"Order + Number = Geometry."

This means if you know which events come before which (the causal order) and how many there are (the number of elements, or their density), you can reconstruct the geometry of spacetime; its shape, dimension, and even its curvature.[2, 3]

The Building Blocks of Reality

Formally, a **causal set** (or **causet**) is a set of "spacetime atoms" that are **partially ordered**. This "partial" ordering is key: it means that some events are causally related (A can cause B, or B can cause C), while others are not (A and C might be "spacelike separated," meaning neither can cause the other, as a light signal wouldn't have time to travel between them).

This ordering relation, $\prec$, encodes causality: $A \prec B$ means event A could have causally influenced event B. This structure must obey three simple rules: [1, 4]

- **Reflexivity:** Every event is related to itself ($A \prec A$). (Some authors adopt an irreflexive convention; the distinction is one of definition and does not affect the physical content.)
- **Antisymmetry:** If $A \prec B$ and $A \neq B$, then B cannot precede A (this is the rule of "cause and effect," which forbids time travel loops).
- **Transitivity:** If $A \prec B$ and $B \prec C$, then $A \prec C$ (causality is a chain; if A causes B, and B causes C, then A is also a cause of C).

At this fundamental level, there are no coordinates (like x, y, z), no distances, and no smooth time. There is only **order**. Each event corresponds, on average, to a spacetime volume of order one Planck volume (10^{-105} m^3). Geometry is not put in by hand; it *emerges* from the relationships between these events.

We can visualize these structures as **Hasse diagrams**. Each dot is an event, and lines are drawn only between events with a direct causal link (with no event in between). Time, in this picture, generally flows upward on the page. This simple "connect-the-dots" diagram is the fundamental structure of spacetime. [1, 4]

From Atoms to Cosmos

How do we get from this abstract set of dots and arrows back to the smooth, 4-dimensional spacetime we observe?

Sprinkling

CST proposes that our continuous manifold approximates an underlying discrete causet, like a high-resolution digital image that appears perfectly smooth from a distance but is composed of individual pixels. To connect the two, CST uses a process called "sprinkling."

Imagine randomly scattering a huge number of points (events) into a continuous spacetime manifold, like dust motes in a sunbeam. This process is governed by a **Poisson distribution**, which is a mathematical model for the random scattering of points, without any pattern or clumping. This is crucial: a truly random "sprinkling" is Lorentz invariant. This is a powerful concept from Einstein's relativity: all observers, no matter how fast they are moving, will agree on the statistical properties of the scattering. It does not create a preferred reference frame or direction (like a fixed crystal grid in space), preserving Einstein's core principle; a hurdle where many other discrete-spacetime theories stumble. [1, 3, 4]

The *hauptvermutung* (main conjecture) of CST is that this relationship works both ways: a causal set, if it is the right type, is conjectured to determine its corresponding large-scale spacetime geometry.

Coarse-Graining and Emergent Dimension

At our large scale, we never see the individual "pixels" of spacetime. We only see a coarse-grained average of countless events; just as we see a smooth-looking photo, not the individual dots of ink.

A key test for the theory is whether it can recover the properties of our universe from the causet structure alone. One of the most striking successes is **dimension estimation**. Physicists have developed mathematical tools that, by analyzing only the network of causal links (e.g., counting how many events are in a given "causal interval"), can determine the effective dimension of the spacetime the causet approximates. For causets "sprinkled" into 4D spacetime, these estimators correctly return the answer: 4. [4, 5, 6]

In CST, spacetime's smoothness, curvature, and even its dimensionality are not fundamental. They are **emergent statistical properties** of this underlying discrete network. "Wetness" is a good analogy: a single water molecule isn't wet. "Wetness" is a property that emerges from the collective behavior of countless molecules. CST suggests "dimension" is the same kind of emergent idea.

Problems: Dynamics and Selection

This picture is elegant, but it faces two enormous challenges.

The Vast Space of All Causal Sets

The number of possible causal sets is astronomically vast. The vast majority of them look nothing like our smooth, 4D universe. They are wild, tangled, and "pathological"—often called **Kleitman-Rothschild causets**—and lack any regular, manifold-like structure. They overwhelmingly fail to exhibit manifold-like structure.

The challenge is to find a **selection principle** that explains why our universe is one of the very special, well-behaved ones. This requires a **theory of dynamics**—a rule for how the causal set grows. [7, 9]

How Does the Universe Grow?

If the universe is a growing causet, what is the law of its growth? This is the central, unsolved problem in CST. There are several promising approaches:

- **Classical Sequential Growth (CSG):** In this model, championed by Fay Dowker at Imperial College London, the universe grows event by event[7, 9]. At each step, a new event is "born" and forms causal links to existing events, creating the future. The rules of this growth are **stochastic** (random but governed by probabilities) and must, at a large scale, reproduce the dynamics of general relativity. In this picture, Einstein's equations would plausibly emerge as an effective thermodynamic law for spacetime rather than a fundamental one. This is like the laws of temperature and pressure for a gas: they are an average, statistical description of countless atoms, not a rule that applies to each atom individually.
- **Quantum Sequential Growth (QSG):** This approach treats the growth process itself quantum-mechanically. Instead of a single history, the universe evolves as a **superposition** (a quantum state of "all possibilities at once") of all possible growth histories, which interfere with each other.
- **Sum-over-Histories:** This mirrors Richard Feynman's **path integral** formulation of quantum mechanics. In that view, a particle gets from A to B by "sniffing out" *all possible paths* at once. In CST, one would define a "quantum action" for every possible causet and "sum" over all of them. The universe we experience would be the one that emerges from the constructive interference (where the paths "add up" and reinforce each other) of all possible causal set histories. [4, 9]

Defining these dynamics in a consistent, computable way remains the theory's Holy Grail.

How CST Stacks Up

Causal Set Theory's minimalism sets it apart from its more famous competitors.

Unlike **String Theory**, which posits exotic new entities (vibrating strings) and fundamental symmetries (supersymmetry) in a higher-dimensional background spacetime, CST is radically simple. It requires no extra dimensions and no new particles, only the bare-bones concepts of events and causal order.

Unlike **Loop Quantum Gravity (LQG)**, which quantizes Einstein's equations directly to create discrete "atoms of space" or "quanta of volume," CST takes a different approach. In LQG, geometry is fundamental (though it becomes "chunky"). In CST, geometry is **emergent**. The most fundamental concept is causal order, from which space, time, and even dimension must arise.

The Payoff: Testable Predictions

For decades, quantum gravity has been a purely theoretical game. But CST is beginning to make contact with the real world, offering tantalizing—and testable—predictions.

The Cosmological Constant

One of the most intriguing phenomenological successes of CST is its prediction of the **cosmological constant** (Λ), the mysterious "dark energy" that is accelerating the universe's expansion. This is one of the biggest mysteries in physics, as QFT predicts a "vacuum energy" that is 120 orders of magnitude larger than what is observed. In a stunning calculation, Rafael Sorkin argued that if spacetime is a causet, fundamental quantum fluctuations in the number of spacetime atoms would lead to a tiny, residual energy in the vacuum [8]. This simple model naturally predicts a small, positive cosmological constant that is of the correct observed order of magnitude. It is one of the very few approaches that produces the correct order of magnitude without fine-tuning.

The Photon Race

Many discrete-spacetime theories predict that the "graininess" of space would affect the propagation of light, much as a rocky beach slows down a wave differently than open water. High-energy photons (with short wavelengths that "feel" the graininess) might travel at very slightly different speeds than low-energy photons. Observations of distant gamma-ray bursts (which release photons of many energies at once) have so far found no such discrepancy [11, 10].

Here, CST has a clever answer. Because its "sprinkling" process is explicitly Lorentz invariant (it looks statistically the same to all observers), CST predicts that this will *not* happen. All photons, regardless of energy, should travel at the same speed. In this case, a "null" result—finding no variation in the speed of light—is a positive prediction in favor of the theory.

Beyond the Continuum: A New Intuition

If Causal Set Theory is correct, it invites us to adopt a new and profound intuition for reality. The universe is not a static "4D block" (the "block universe" view, where past, present, and future all exist "at once") that we move through. Instead, the universe is the act of time unfolding, event by event, in a process of "becoming." The ultimate fabric of the cosmos is not space, but the growing, branching web of cause and effect.

Perhaps the deepest lesson of CST is philosophical: that **events, not objects, are fundamental.** The world is a process, not a thing. [4, 12]

Causal Set Theory is not yet a complete theory of quantum gravity. Its mathematical and conceptual hurdles are immense. But it offers something precious: a simple, logical, and consistent idea that tackles the problem of spacetime head-on. It tells us that beneath the smooth curves of Einstein's geometry lies a discrete rhythm—a hidden causal melody that composes the cosmic symphony itself. This interpretation is not unique to CST and remains a matter of ongoing philosophical debate.

Conclusion

Causal Set Theory remains an unfinished approach to quantum gravity. It lacks a complete quantum dynamics, faces deep challenges in explaining why our universe is manifold-like, and has yet to make decisive experimental contact. In this respect, it is best understood not as a final theory, but as a principled framework still under construction.

Its enduring value lies in its radical clarity. By insisting that causality and discreteness are fundamental, Causal Set Theory forces us to reconsider what spacetime itself is, rather than how to quantize familiar geometric structures. Whether or not it ultimately succeeds, it sharpens the questions that any viable theory of quantum gravity must confront—and that alone makes it an idea worth taking seriously.

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The European Robin's Quantum Secret

V S Abhishek

On a hot September afternoon, Dr Bera entered the lecture hall for the quantum mechanics class, clutching a coffee mug in his hand. He began discussing the various fields where quantum mechanics is applied and observed in the real world. He asked a simple question - how do birds like the European robin travel across the world in the correct direction without having a map or compass? Is it not something to ponder upon? A few students replied that, probably, the bird navigates with the help of the Earth's magnetic field. However, Dr Bera argued that the Earth's magnetic field (roughly fifty microteslas in strength) is far too weak to affect ordinary chemical bonds noticeably. For a better perspective, a typical refrigerator magnet is about 1,00,000 times stronger.

But somehow, these birds do indeed detect this faint whisper of a field and use it to navigate. When we think about it, migration is truly one of nature's most astonishing phenomena. Tiny birds like robins travel thousands of kilometres, across oceans, mountains, and continents, without any navigation instruments. Some return to the same nesting site every year with astonishing precision. For a long time, scientists had assumed that birds use the Sun, stars, and geographic landmarks to guide them, but these cues disappear on cloudy nights or under dense forest canopies. Yet, these birds still manage to stay on course. How can biology achieve what even human-made sensors struggle to do?

Quantum Magnetoreception

This question lingered with me because, during that time, I was in the midst of reading "Quantum Aspects of Life" by Sir Roger Penrose. Klaus Schulten, a renowned biophysicist, also believed that the magnetic field enters and initiates a cascade of chemical reactions in their eyes, which guide them in navigating their travel. However, this claim was later disproved by demonstrating that, to form bonds within molecules, the energy required should be greater than thermal energy. In contrast, the energy obtained from the Earth's magnetic field was found to be a million times less than the thermal energy. Schulten saw this case as a balancing act. Suppose a coin is placed on a table such that 90% of it lies on the table and 10% off the edge. Now, if a mosquito sits on the 10% area, it is unlikely for the coin to fall. But if we had 60% off the edge (it's on the verge of falling) and 40% on the table, the coin will definitely fall. If it is in a highly influential state, even minor changes can significantly impact the state of larger things. Schulten was interested in finding the chemical equivalent of this.

The Radical Pair Mechanism

Quantum mechanics provides such a delicate mechanism through radical pairs. Radicals are formed when a photon of light is absorbed by a molecule, leading to a split into two fragments. Each fragment (or radical) has an unpaired electron. These two unpaired electrons can possibly stay in two quantum spin states: a singlet state, where the electrons have antiparallel spins or a triplet state, where the electrons have parallel spins. The energy difference of singlet and triplet states is extremely small; they can oscillate coherently between the configurations several times per second through a process called quantum spin coherence.

Interestingly, the usual coherence decay is on the order of picoseconds in warm, wet environments, such as cells. But in radical pairs inside a bird's retina, experiments suggest coherence can last microseconds, long enough for the Earth's tiny magnetic field to influence the reaction. If the singlet and triplet states lead to different chemical reaction pathways, then the yield of the reaction products will depend on the orientation of the radical pair relative to the magnetic field. This orientation dependence effectively provides a directional (compass-like) signal, allowing the European robin to detect changes in the geomagnetic field through light-dependent chemical reactions in its body, likely in the retina.

Experimental Evidence

A major breakthrough came in 2008 when Maeda, Henbest, Hore, and collaborators demonstrated a proof-of-principle chemical compass. They studied an artificial molecular triad composed of carotenoid, porphyrin, and fullerene (CPF). These artificial molecules mimic photosynthetic reactions in plants and bacteria.

Upon excitation with short laser pulses, CPF formed radical pairs whose reaction yields were measurably affected by magnetic fields even weaker than Earth's. These radical pairs had a lifetime of about 100 nanoseconds. This experiment established, for the first time, that a chemical system can exhibit directional sensitivity to weak magnetic fields, confirming the feasibility of a chemical (radical-pair-based) magnetic compass, even though the molecule used was not biologically derived.

Quantum Coherence in Biology

Maintaining quantum coherence in such an environment is nothing short of a grand feat. Quantum computers, built in carefully isolated cryogenic conditions, struggle to maintain coherence for even a few microseconds. Yet, evolution seems to have engineered molecular structures capable of achieving similar coherence times at the standard body temperature.

Researchers propose that the specific geometry of the cryptochrome molecule, a light-sensitive protein found in bird retinas and its surrounding protein environment, shields the spins from random collisions. Some even speculate that vibrations within the molecule, far from destroying coherence, may help maintain it through subtle resonance effects.

The two electron spins in a radical pair are quantum-entangled, meaning their states remain correlated. Either exceptionally slow decoherence or extraordinary magnetic sensitivity—or both—must be at play.

Implications and Outlook

The avian compass is now regarded as one of the best candidates for quantum effects playing a functional role in living organisms. But it is not alone. Photosynthetic bacteria and plants use quantum coherence to efficiently transfer energy during light harvesting. Some theories of smell propose quantum tunnelling of electrons as a mechanism for odour detection. Enzyme reactions sometimes rely on quantum tunnelling of protons. If these mechanisms are truly quantum, it suggests that life doesn't merely adapt to quantum mechanics; it uses it. Biology, chemistry, and physics merge into a single narrative: evolution has harnessed quantum rules to achieve precision, efficiency, and sensitivity that classical systems could never attain.

Reflecting on that afternoon with Dr Bera, I realise how a simple classroom question, "How do birds know where to go?", opened for me a doorway to one of the most fascinating frontiers of modern science. The robin's flight across continents isn't guided by myth or mystery, but by entangled electrons whispering through molecular structures in its eyes. A single photon striking a molecule might decide the path of a migrating bird. As I read more about the Quantum Aspects of Life, I understand why Penrose was fascinated by such ideas; they challenge our conventional understanding of what life is. If coherence and entanglement can survive in the warmth of a living cell, then perhaps the boundary between physics and biology is not as sharp as we often assume. And so, that afternoon as Dr Bera's voice echoed about quantum mechanics in the real world, I realised something profound: the quantum world isn't confined to laboratories or equations, it lives in every feather, every photon, and every journey across the sky.

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A Conversation with Dr Yogesh Singh

Pranaya Chugh, V S Abhishek, V S Manoj Krishna

Please introduce us to your field of work, Quantum Condensed Matter, and how you came about pursuing it?

Say, you have a collection of particles that are allowed to interact with each other; they can exist in various phases depending on physical parameters like temperature, pressure, etc. The example that we encounter every day is that of water molecules. If you are at a high temperature, the collection forms a vapour. If you cool it down, it becomes a liquid and on further cooling, a solid. Similarly, inside solids, you have electrons that are moving around, and for something like sodium, these electrons behave like a gas of particles that don't interact with each other at all. Whereas in other materials, the electrons can interact very strongly with each other or with other degrees of freedom like atomic vibrations (phonons) or spins. Depending on these interactions, electrons in solids can exist in various phases. Ferromagnets, superconductors, and quantum spin liquids are just a few examples of such phases. Basically, I am interested in looking at the electronic phases of matter inside solids. How I got interested in this area is probably some kind of directed random walk. My father is a theoretical physicist specialising in condensed matter, so physics books, half-written papers, and journals were a constant presence in our home—stacked on tables, always within reach. One specific moment that left a mark stands out in my memory. It was 1986, and I was still in school when high-temperature superconductors were discovered. My father had just returned from a conference about this breakthrough. Normally, he is a quiet, introspective man. However, he had returned from this conference visibly animated, discussing the implications with his colleagues and students over tea or dinners at home. I was of course too young to grasp the details or the implications of what was being discussed. However, fragments of their conversations lingered with me—mysterious phrases like "Cooper pairs" and "cuprates" that maybe sparked a quiet curiosity. Perhaps it was this early exposure that planted the seed of my fascination with the field. Or maybe it was the "proximity effect" of growing up in a family where five relatives were physicists. I have a chacha who retired as an accelerator physicist from BARC Mumbai, and he calls material physicists 'pav bhaji banane wale' because we are seen mixing various elements to come up with interesting materials. But discovering new quantum materials is not always serendipitous. We don't mix things randomly and hope for the best. We need to have an idea, of course. For example, spins inside solids can be loosely visualised as arrows, and in simple situations, they want to either point in the same direction or opposite to each other. Ferromagnets are materials with all spins pointing in the same direction. Now, if you put these spins on a triangle with ferromagnetic alignment, all three spins are happy. However, if you want anti-alignment, then all three spins cannot be simultaneously anti-aligned. This is called magnetic frustration, and as in real life, a little frustration can lead to interesting situations or phases like quantum spin liquids, where the spins do not have any static alignment patterns. So, if one is interested in studying the physics of frustration, we make materials that have spins sitting on lattices with triangular motifs. Therefore, the discovery of novel phenomena in quantum materials is not by serendipity or chance; it is usually by design. We discover quantum materials and phases by design.

Your journey from studying in India to pursuing research abroad in three different countries seems very fascinating. What was this journey like? Was there something you learned along the way?

I was lucky to go to some very good places in India. I did my Master's from IIT Kanpur and then my PhD from TIFR Mumbai. The atmosphere at both these places was very research-oriented. Everybody, including students, was often talking about how they were seeking opportunities after graduation and where they would go for a postdoc, where they would apply, recommendation letters, everything like that. So, this process was ingrained in us, and we were always looking for, not abroad per se, but different environments to work in. One reason people wanted to

Figure 16: Dr Yogesh Singh (on the left) on the terrace of the Brahmagupta hostel at TIFR Mumbai in 1999 with his IITK batchmates Sanjeev and Rajesh. Incidentally, Sanjeev is also a colleague at IISER Mohali now.

go abroad was the difference in work culture. Physics research in Western countries (USA, UK, Europe) typically offers more funding, infrastructure, and an internationally diverse group to work in. While India is rapidly improving, it still faces systemic challenges. Infrastructure is uneven across institutions, with only premier institutes like IISc, TIFR, and IITs having the money to maintain world-class experimental labs. While funding is improving, it remains limited and bureaucratically constrained. Another thing is that while abroad, as a postdoc, completely free of the responsibility of leading a group or of any administrative responsibilities one might be expected to take up in an Indian institute, one feels free to just pursue your ideas. I think that freedom is also available in larger amounts abroad. Therefore, we always wanted to go abroad to taste the different work cultures. Even within Germany and the US (having worked at both places), the work culture varies. As a specific example from my own experience, every group in the Ames National Laboratory in the USA, where I went for my first postdoc, had an institute credit card. So, if you break something in the lab, you could use the credit card to purchase the item with very little red tape. However, if the same thing happened in MPI Dresden in Germany, they would encourage you to try and fix it first. It is not like they have any less money; they just promote a different work culture. Therefore, going to different places to work gives you a broader perspective, and with all these experiences, when you come back to India to start your own group, you are better equipped.

Was the plan of coming back to India always on your list?

Everyone's journey is a random walk. You hardly ever plan for what you will do in life, in the long term at least, and even if you do, life has a way to derail the best-laid plans. Like, I wanted to be in the army when I was about to graduate from school. Never happened for various reasons. Back to how I came to be in an IISER: When I was in my second post-doc as a Humboldt fellow at the University of Goettingen, the IISERs were announced. In India, there was a disconnect between undergraduate teaching and high-end research, and the IISERs bridged this gap. A lot of us realised that IISERs were going to be game-changers in Indian science education because they promised to integrate world-class research with undergraduate learning, foster interdisciplinary thinking, and nurture scientific curiosity from an early stage. Therefore, that was a big attraction for Indian postdocs who were working abroad. We were ripe at the time and were promised that we would be able to teach. Involving undergraduate students in research was only done in the UK and the US at the time, so the fact that it was happening in India was very exciting. If the IISERs had not been announced at that time, I don't think I would have decided to come back. That research was going to be as important as teaching became apparent when I was given a generous budget for setting up my lab in the initial days, which I might not have received at institutes such as IITs. So it was a case of the IISERs happening at the right time, and I took the opportunity.

How early on should one start working in their field? In your opinion, is switching fields at a time 'too late' recommended?

I don't assume to know about other fields, but Physics, fundamentally, is an experimental discipline. If you intend to pursue it as a serious career option, early exposure to hands-on work is crucial. Undergraduates should ideally have access to tinkering facilities where they can freely work with electronics or machine and fabricate small mechanical parts with lathe machines, milling, or 3D printers. Look, changing fields is a classic double-edged sword. If you've spent a good chunk of time in a discipline but it's not lighting a fire in you anymore—or worse, it's making you miserable—you absolutely should not force yourself to stay. Happiness is the priority; switching is a good move if you're unhappy. Take my friend: he got his PhD in Nuclear Physics and laser-atom interactions. By the end, he realised the career path wasn't exciting him and didn't offer the opportunities he wanted, so he decided to jump to cold atoms. Naturally, applying for postdocs abroad with a nuclear physics degree was tough; he got rejected everywhere. Instead of giving up, he took a postdoc at TIFR in a lab that pioneered Bose-Einstein condensation in India. It took him three focused years to master the new field, get his first publications, and now? He's a faculty member in Birmingham and is a recognised spokesperson for atomic clocks, and has even been interviewed on the BBC about his research. The bottom line is that you can indeed be successful after a switch, but you have to use the transition period very efficiently. Your motivation to switch shouldn't be superficial but must come from genuine excitement for the area you are switching into. For me, my lab is my "happy place." When things are stressful at home or academically, I come here. Talking to my students about new results calms me down. Your job should be your stress-buster, not your headache.

Did you have any "Eureka!" moments during your research work?

Yes, I had two Eureka moments in my career. I talked about quantum spin liquids, right? Let me first explain what is so exciting about such phases. For about a hundred years, phase transitions and phases in general were classified in the Landau paradigm. So, for example, if you sit inside the ocean and look around, not just with human eyes but with a powerful microscope, you will not see any structure. Everything is isotropic and homogeneous. But if we cool water, it freezes into ice. If you repeat the experiment, you will now see a definite pattern in the arrangement of molecules. So, the freedom that the water molecules had in the liquid phase is lost, and some symmetry is broken. So, ever since the mid-1930s, when Landau set these ideas on paper, people have been understanding the phases and the transformation between phases in this language. Now, in the last 20-30 years, several phases have been discovered that do not fall into this paradigm. There is no order parameter and no symmetry breaking. So, how do you classify these phases? These are called topological phases of matter, and quantum spin liquids are an example of them. One of my Eureka moments happened when I synthesised crystals of the first Kitaev material Na_2IrO_3 with a graphene-like lattice. To put its importance in context, the Kitaev model is for quantum spin liquids what the Ising model is for classical magnets. I was the first to find a material realisation of this model in the world. The other eureka moment was when I discovered a different spin liquid material $Ca_{10}Cr_7O_{28}$ with a kagome lattice. As I mentioned before, typically, researchers induce a quantum spin liquid state by placing spins on triangular lattices that promote frustration through antiferromagnetic interactions. What made this new material so remarkable was that it hosts dominant ferromagnetic interactions, therefore requiring us to propose a completely new mechanism to account for its quantum spin liquid phase.

If money and funds were no object, would there be something you'd like to explore or improve?

I do not know if I have a wish list, but there are some critical infrastructure gaps in India, particularly in my area of research, which require neutron scattering and diffraction. The existing facilities, such as those at BARC, provide only a weak neutron flux. This forces one to use a significantly larger sample volume to obtain a clear signal. However, the materials we study are extremely expensive, costing around ¤1 lakh per gram. This high material cost, coupled with the low-flux facilities, makes neutron scattering experiments we would like to do financially unviable in India. On the other hand, equivalent facilities abroad allow us to measure the same data using just a 100-milligram sample. Neutron facilities are just one example. I also need access to high-quality synchrotron facilities, muon facilities, and other advanced facilities. Also, as low-temperature physicists, we need liquid helium to run our experiments. Liquid helium is becoming scarce because we used to import it from Russia and the US. Now, because big companies like Google have begun research in quantum computing, they need to run dilution refrigerators. So, they need all the helium that America is producing, and ultimately, we are not getting any helium at all. Although extremely difficult, if India could develop technology to extract and purify helium, it would be great.

What's your advice for a young experimentalist? What mindset should they begin their career with?

The only rule in my lab is: don't be afraid to make mistakes. Every student that I have had has either broken something or made errors in the lab, and I've never looked at it as a loss. I have done the same thing in my student days. That's how you learn and grow. Also, while you chase your great ideas, which may be high-risk, high-reward ones, also keep in mind that it's important to have a steady supply of good ideas or what I like to call "low-hanging fruit". I feel that it is risky and maybe even irresponsible to put a student's career at stake by committing them to only a high-risk project for which the timelines and outcomes could be uncertain. It's important to have trustworthy ideas and a lot of such ideas. Being successful in research comes from being consistent and dedicated rather than having brilliant ideas every time. So dedicated persistence and a belief in your underlying ideas will inevitably lead to success. The Eureka moments are very rare; you will probably only get one or two in a lifetime. But if you consistently do the right process, you will continue to produce good work. My success will also be measured by how my students do. My job is to try to produce good students and furnish them with good experimental science practices. That's how I see my training of students. We provide them with a nest, a safe space to learn until they're ready to take their flight and embark on their own careers.

Do you have a message for the readers, students, and the people in your life?

As a faculty member in India, one is wearing multiple hats. You are a teacher and a mentor to students, a colleague to your fellow faculty, a member in various administrative committees, but you are also a parent and a spouse. Striking that balance between the professional and the personal is very important. I think I have been able to keep a very good balance of these things, and therefore, I owe a lot to my family because I'm often here on weekends, so I must thank them for giving up their share of my time. I have tried to take inspiration from senior colleagues and especially learn from the wonderful balance shown by my female colleagues, who are skillfully managing the added responsibilities of home and family alongside their careers. I look at seniors like Sudeshna, for instance! She still publishes tons of research—often more than the younger colleagues in the department—which just goes to show that one can absolutely find work-life balance. I can happily claim to have found the sweet spot to be able to balance all these aspects of my life.

How Time Became Crystalline ?

Sipra Subhadarsini Sahoo

Time crystals represent a fundamentally new phase of matter in which time-translation symmetry is spontaneously broken, giving rise to persistent periodic motion even in a system's lowest-energy state.Originally proposed as a temporal analogue of spatial crystals, time crystals challenge conventional notions of equilibrium, stability, and dynamical behavior.Early attempts to realize such phases in classical equilibrium systems were ruled out by no-go theorems, but the concept found renewed viability in non-equilibrium and quantum many-body settings.This article traces the evolution of time crystals from their theoretical origins in classical and quantum mechanics to their first experimental realization in driven quantum systems.It further explores modern developments, including time crystal optomechanics, quantum simulation of complex networks, and applications in precision sensing and quantum information.By situating time crystals within the broader landscape of symmetry breaking and non-equilibrium physics, the article highlights their significance as both a conceptual breakthrough and a promising platform for future quantum technologies.

Introduction:

Atoms in an ordinary crystal arrange themselves in a repeating pattern in space.This spatial periodicity-snowflakes, salt crystals, diamond lattices,etc is one of the most familiar manifestations of broken symmetry in physics.But what if nature allowed an even stranger possibility?

What if matter could arrange itself periodically in time? This introduces a counterintuitive central idea :a system exhibiting **perpetual motion in its lowest energy state**.This proposition might appeal to our classical intuition as a violation of the fundamental laws of thermodynamics and to the very nature of equilibrium.In 2012, however, this paradoxical concept was brought into the mainstream by **Frank Wilczek and Alfred Shapere**, who proposed that time-translation symmetry-the invariance of physical laws under shifts in time-could be spontaneously broken.

To bridge the gap between intuition and theory, let's consider the formation of spatial crystals. If we define $\phi(x)$ as an angular variable, we can construct energy functionals where the minimum energy occurs not at rest, but at a constant gradient. For instance:

$$V_1(\phi) = -\kappa_1 \frac{d\phi}{dx} + \frac{\lambda_1}{2}\left(\frac{d\phi}{dx}\right)^2$$

$$V_2(\phi) = -\frac{\kappa_2}{2}\left(\frac{d\phi}{dx}\right)^2 + \frac{\lambda_2}{4}\left(\frac{d\phi}{dx}\right)^4$$

For positive coefficients, these systems reach their lowest energy states when:

$$\frac{d\phi_1}{dx} = \frac{\kappa_1}{\lambda_1} \quad \text{and} \quad \frac{d\phi_2}{dx} = \pm\sqrt{\frac{\kappa_2}{\lambda_2}}$$

By replacing the spatial derivative with a temporal one ($\dot{\phi}$), Wilczek and Shapere hypothesized that a conservative, time-independent system could trace a closed trajectory even in its ground state.While the suggestion of a "moving ground state" immediately raised tensions regarding the definition of perpetual motion and the topology of phase space, it ignited a conceptual revolution. This journey from a controversial "no-go" to a verified phase of matter represents one of the most transformative shifts in modern condensed matter physics.

What Is a Time Crystal? Breaking Symmetry in Time:

To define a time crystal, one must first reconsider the fundamental nature of stability and equilibrium.In classical thermodynamics, any system left to its own devices is expected to settle into a static "ground state" where macroscopic motion ceases and time-translation symmetry remains intact.A time crystal, however, represents a defiant exception: a unique phase of matter that exhibits spontaneous temporal periodicity.First hypothesized by Nobel laureate **Frank Wilczek** in 2012, these systems maintain a constant "ticking" even in their lowest energy state, oscillating between configurations indefinitely without requiring an external energy source.This behavior occurs because the system spontaneously breaks continuous time-translation symmetry, reducing it to a discrete subgroup, a temporal analog to how a liquid freezes into a spatial crystal by breaking spatial translation symmetry.

Unlike a clock or a pendulum, which eventually dissipate energy due to friction and other resisiting forces, a time crystal exists in a state of dynamic equilibrium.It does not "settle" because its internal quantum dynamics that prevent it from thermalizing or heating up.This leads to a fascinating paradox: a system that is fundamentally stable and yet remains in constant motion.While early "no-go" theorems initially suggested such a state was impossible in equilibrium, the discovery of non-equilibrium quantum systems provided the necessary loophole.By 2017, experimentalists successfully realized these phases in trapped ions and spin chains, proving that robust temporal order is not merely a theoretical curiosity but a tangible, realizable frontier of condensed matter physics.

Classical Time Crystals: [1]

The theoretical genesis of time crystals lies in a direct challenge to the Hamiltonian constraints of classical mechanics, which typically mandate that energy minima coincide with stationary configurations.In any smooth, conservative system, the canonical equations of motion $\dot{p}_j = -\partial H/\partial q_j$ and $\dot{q}_j = \partial H/\partial p_j$ necessitate that all velocities $\dot{q}_j$ vanish at a local energy minimum.To circumvent this "at-rest" requirement, Wilczek and Shapere introduced the concept of singular Lagrangians, where the correspondence between conjugate momentum (p) and velocity ($\dot{\phi}$) is non-monotonic.By considering a quartic kinetic model $L = \frac{1}{4}\dot{\phi}^4 - \frac{\kappa}{2}\dot{\phi}^2$, they demonstrated that the energy is minimized not in a static state, but at a non-zero velocity defined by $\dot{\phi} = \pm\sqrt{\kappa/3}$.This phase-space transition manifests as a **swallowtail catastrophe**,a mathematical singularity where the energy H, as a function of $p = \dot{\phi}^3 - \kappa\dot{\phi}$, becomes multi-valued.At these singular cusps, the standard requirement for a vanishing gradient is waived, providing a stable loophole for a moving ground state that remains energetically favorable.

This phenomenon finds a more robust realization in the **Double Sombrero model**, which utilizes a complex scalar field $\psi = \rho e^{i\phi}$.Under the Lagrangian $L = \frac{1}{4}(\dot{\rho}^2 + \rho^2\dot{\phi}^2 - \kappa)^2 - V(\rho)$, the system is energetically driven toward a persistent circular trajectory when ρ is fixed at its potential minimum.This spontaneous breaking of continuous time-translation symmetry does not result in total disorder; rather, it yields a "locked" symmetry, where the system remains invariant under a combined operation of time translation and internal phase rotation.Such a configuration effectively bridges the gap between abstract group theory and physical dynamics, manifesting internal cyclic motion as a stable, macroscopic order in the fourth dimension.This classical foundation paved the way for modern non-equilibrium quantum realizations, proving that matter can indeed possess a periodic rhythm of its own.

From Theory to Reality:The First Experimental Time Crystal [3]

The long-standing theoretical idea of time crystals crossed from speculation into experimental reality in 2017, with the first direct observation of a discrete time crystal reported by **Christopher Monroe** and collaborators at the University of Maryland and the National Institute of Standards and Technology.The experiment was conducted in a precisely controlled chain of trapped ytterbium ions, where the system was subjected to a periodic (Floquet) drive under conditions of strong interactions and many-body localization.These non-equilibrium conditions were essential, as they prevented the system from absorbing energy from the drive and heating up, which would otherwise destroy temporal order.Instead, the ions exhibited a robust subharmonic response, oscillating with a period twice that of the external drive, thereby spontaneously breaking discrete time-translation symmetry.Crucially, this temporal order persisted despite imperfections and perturbations, demonstrating that the observed behavior was not a trivial driven oscillation but a genuine new phase of matter.This experiment provided the first concrete evidence that time crystals can exist in nature ,not in equilibrium systems, as originally envisioned, but in driven quantum systems,marking a decisive shift from theoretical debate to experimental confirmation of temporal order in many-body physics.

Quantum Time Crystals: [2]

Quantum time crystals represent a paradigm shift in which spontaneous symmetry breaking occurs in the temporal dimension within closed quantum systems.Unlike ordinary crystals, which break spatial translation symmetry, quantum time crystals break time-translation symmetry ($\mathcal{T}$), leading to the spontaneous emergence of periodic motion in an otherwise time-invariant dynamical system.This concept was first proposed by **Frank Wilczek** and demonstrated that temporal order can arise without violating the principles of quantum mechanics.

The Ring Particle Model

Wilczek resolved the apparent contradiction between time-dependent behavior and energy eigenstates by exploiting observables that are not generated by single-valued operators.A canonical example is a charged particle constrained to move on a ring of unit radius threaded by a magnetic flux α.The Hamiltonian of the system is given by

$$H = \frac{1}{2}\left(\pi_\phi - \alpha\right)^2.$$

The energy eigenstates are labeled by integers l, with energies

$$E_l = \frac{1}{2}(l-\alpha)^2.$$

For non-integer values of α, the ground state corresponds to an integer l_0 that minimizes $(l-\alpha)^2$, and the expectation value of the angular velocity is

$$\langle l_0|\dot{\phi}|l_0\rangle = l_0 - \alpha \neq 0.$$

Thus, the lowest-energy state carries persistent motion.This phenomenon is directly analogous to persistent currents in superconducting rings and demonstrates that quantum systems can exhibit motion in their ground state without violating energy conservation.

Interacting Many-Body Systems and Solitons

To establish genuine spontaneous symmetry breaking, Wilczek extended the construction to interacting many-body systems.Considering a large number of particles on a ring with weak attractive interactions, the system admits a mean-field description governed by a nonlinear Schrödinger equation,

$$i\frac{\partial\psi}{\partial t} = \frac{1}{2}\left(-i\frac{\partial}{\partial\phi} - \alpha\right)^2\psi - \lambda|\psi|^2\psi,$$

where $\lambda > 0$ characterizes the attractive interaction strength.

When the coupling λ exceeds a critical threshold, the uniform density configuration becomes energetically unfavorable.Instead, the ground state forms a localized density profile-a soliton, that moves uniformly around the ring.This motion breaks continuous time-translation symmetry down to a discrete subgroup.In the thermodynamic limit ($N \to \infty$), different time-shifted configurations become orthogonal, ensuring the robustness required for spontaneous symmetry breaking.

These results established that temporal order in quantum ground states is theoretically consistent and physically meaningful.Although the original constructions were idealized, they laid the conceptual groundwork for the later experimental realization of discrete time crystals in driven, non-equilibrium quantum systems.

Why Time Crystals Matter:Applications and Emerging Technologies

The discovery of time crystals represents more than just a theoretical curiosity;it offers a new paradigm for understanding phases of matter and provides a versatile platform for next-generation quantum technologies.By breaking time-translation symmetry, these systems maintain long-term coherence, allowing them to serve as stable instruments in environments where traditional quantum states would rapidly decohere.

Quantum Simulation of Complex Networks

Time crystals offer a unique application as quantum simulators for complex, large-scale networks.By mapping the effective Hamiltonian of a discrete time crystal (DTC) onto a graph, researchers can visualize and characterize the crystalline order through graph theory.

- **Preferential Attachment:** During the “melting” of a time crystal, the system’s network evolution exhibits an emergent preferential attachment mechanism.
- **Scale-Free Networks:** This mechanism leads to the formation of scale-free networks, which are characterized by power-law degree distributions ($p(k) \propto k^{-\beta}$).
- **Platform Versatility:** These simulations can be performed on noisy intermediate-scale quantum (NISQ) platforms, such as superconducting qubit chips or trapped ion chains.
- **Cross-Disciplinary Use:** This application allows for the study of complex structures found in biological neural networks, social systems, and communication infrastructures within a controlled quantum environment.

Time Crystal Optomechanics

A revolutionary application involves coupling continuous time crystals (CTCs) to macroscopic mechanical oscillators, creating a “time crystal optomechanics” platform.This hybrid system combines the inherent coherence of a time crystal with the high-precision sensitivity of traditional optomechanical systems.

- **Coupled Dynamics:** In a magnon-based time crystal trapped in superfluid ^{3}He, the time crystal frequency ω_{TC} is modulated by the position of a mechanical resonator, such as a surface gravity wave.
- **Precision Spectroscopy:** This setup paves the way for ultra-precise spectroscopy and the measurement of weak forces in regimes previously inaccessible to standard optomechanics.
- **Tunability:** The coupling can be tuned from quadratic to linear by adjusting the effective static tilt (θ_o) of the mechanical surface.

Quantum State Storage and Sensing

The robustness and "rigidity" of time crystals make them ideal candidates for quantum information tasks.

- **Robust Quantum Memory:** Due to their ability to resist external perturbations, time crystals could be used to implement stable quantum memory for storing information over long coherence times.
- **Topological Defect Detection:** Using time crystal optomechanics as an instrument allows for the detection of topological defects and potentially even dark matter research in topological superfluids.
- **Quantum Walks:** Structural information about complex networks can be experimentally obtained by exploiting quantum walks within the time crystal's configuration space.

Beyond the Horizon:Current Frontiers and Future Directions

The transition of time crystals from theoretical provocations to experimentally realized phases of matter has opened a new frontier in non-equilibrium physics.Current research has progressed beyond simple observation toward the integration of these phases into complex hybrid architectures, where their inherent long-range temporal order provides a unique advantage for quantum control and precision measurement.

Current Frontiers

- **Time Crystal Optomechanics:** Researchers have successfully coupled continuous time crystals (CTCs) formed of magnons in superfluid ^{3}He to macroscopic mechanical resonators.This coupling follows a predominantly quadratic optomechanical-like Hamiltonian:

$$\hat{H}_{int} = 2\pi\hbar g_2 \hat{a}^\dagger \hat{a}(\hat{b}^\dagger + \hat{b})^2$$

- This architecture enables the use of time crystals to characterize mechanical modes in ultra-low temperature regimes, providing insights into dissipation mechanisms like scattering from thermal excitations or surface-bound Andreev states.
- **Scale-Free Network Simulation:** The melting process of discrete time crystals (DTCs) is being used to simulate complex quantum networks.By analyzing the Floquet graph of these systems, scientists have identified an emergent preferential attachment mechanism that gives rise to scale-free network structures.

Future Scopes

- **Robust Quantum Technologies:** The "rigidity" and persistent coherence of time crystals,capable of maintaining stable oscillations for up to 10^8 cycles,position them as ideal candidates for robust quantum memory and state storage.
- **Precision Sensing and Fundamental Physics:** Future applications include utilizing time crystal optomechanics for the detection of topological defects and potentially as sensors for axion wind or other dark matter candidates in topological superfluids.
- **Enhanced Coupling Regimes:** The next generation of devices seeks to replace surface waves with nanoelectromechanical resonators to reach the strong-coupling regime.This may eventually allow for the observation of the mechanical dynamical **Casimir effect** and other unexplored regimes of quantum optomechanics.

The discovery of time crystals is not the culmination of a decade of research, but the beginning of an era where temporal order is manipulated with the same precision as spatial structure.

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Why Sheldon Couldn't Stop Guessing Quark-Gluon Plasma

And Why You Should Know What It Is

Damini Das

Introduction

If you've watched *The Big Bang Theory*, you might remember this hilarious scene: the gang is playing Pictionary, Leonard draws a circle with dots inside, and before he can finish, Sheldon blurts out,

"It's a Quark-Gluon Plasma... it's asymptotically free partons inside a Quark-Gluon Plasma!"

completely ignoring Leonard's frustrated reply:

"It's a cookie, Sheldon... it's a cookie."

For most people, it's just a funny line. But what **is** a Quark-Gluon Plasma? And why is Sheldon so obsessed with it?

Well, it's not just a made-up physics buzzword. It's actually one of the **most exotic, mind-blowing states of matter**—and believe it or not, it holds clues to how the **entire universe began**.

Quark-Gluon Plasma

When we talk about Quark-Gluon Plasma (QGP), we're talking about **melting matter at the deepest level**. Normally, **quarks** (the tiniest building blocks of matter) are trapped inside **protons and neutrons**, held together by **gluons**, the carriers of the strong nuclear force.

At extremely high temperatures and densities, such as those that existed microseconds after the Big Bang, the strong coupling between quarks becomes weak, allowing them to behave almost like free particles—a property known as **asymptotic freedom**. In this state, quarks and gluons are no longer confined within hadrons but exist in a **deconfined phase** known as the **Quark-Gluon Plasma**.

Scientists recreate QGP in laboratory conditions using **high-energy heavy-ion collisions** at facilities like the **Relativistic Heavy Ion Collider (RHIC)** and the **Large Hadron Collider (LHC)**. These collisions generate the extreme energy densities and temperatures required to briefly produce QGP, which exists for only about 10^{-23} seconds. While it cannot be observed directly, its existence is inferred from **indirect signatures** such as **collective flow**, **jet quenching**, and **strangeness enhancement**.

Interestingly, recent studies of **high-multiplicity proton-proton (pp) collisions** have shown features similar to those seen in heavy-ion collisions, such as long-range correlations and azimuthal anisotropies. This has sparked a new direction in research, exploring the emergence of **QGP-like effects even in small systems**, further deepening our understanding of **Quantum Chromodynamics (QCD)** dynamics.

Jet Quenching: The Fingerprint of Quark-Gluon Plasma

One of the most exciting signatures of QGP is **jet quenching**. No, it's not about turning off water jets—it's about how **high-energy particle jets lose energy inside the quark-gluon plasma**.

What Are Jets?

In high-energy proton-proton (pp) collisions, high-momentum quarks or gluons are produced during head-on collisions. These partons hadronize and emerge as a **collimated stream of particles known as jets**. Jets serve as useful tools to probe the fundamental building blocks of matter and the strong nuclear force. In heavy-ion collisions, jets help us understand the properties of the hot and dense medium formed after the collision, particularly by studying the **energy loss of partons**.

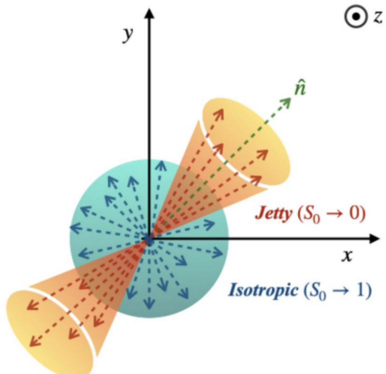

Figure 17: This schematic shows jetty and isotropic events in the transverse plane, assuming the z-axis is the beam axis or the longitudinal axis. Source: https://www.nature.com/articles/s41598-022-07547-z

How ALICE Studies Jet Quenching

At **ALICE** (A Large Ion Collider Experiment) at the **Large Hadron Collider (LHC)**, scientists collide heavy ions like lead nuclei together at nearly the speed of light. In **normal collisions**, jets come out clean and energetic, like water shooting from a hose. But in **heavy-ion collisions**, where QGP forms, these jets **get quenched**—they lose energy, **spread out**, or even **disappear** before exiting the plasma.

Jet quenching is a key signature of QGP formation, where high-momentum partons lose energy via **elastic (collisional)** and **inelastic (radiative)** processes while traversing the dense colored medium. The extent of energy loss is quantified using the **nuclear modification factor**, $R_{AA}(p_T)$, which compares particle yields in nucleus-nucleus collisions to those in pp collisions, scaled by the number of binary collisions. A significant suppression ($R_{AA} < 1$) indicates final-state energy loss in the medium.

Studies also explore **dihadron angular correlations**, showing suppression of the away-side jet in heavy-ion collisions, providing further confirmation of medium-induced energy loss. At the LHC, full jet reconstruction, including dijet asymmetry, provides detailed insight into the transport properties of QGP.

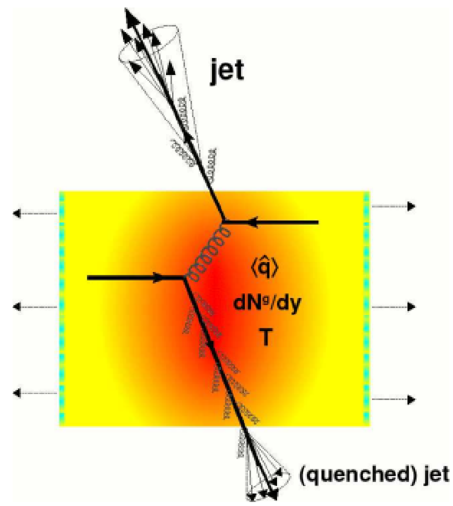

Figure 18: One of the jets is produced near the surface of the hot and dense medium and the other deep inside. The away-side jet gets quenched. Source: https://arxiv.org/pdf/1404.3294

Why It's So Exciting

Jet quenching acts like a **cosmic probe**, offering insights into the **birth of the universe**. Studying these effects helps scientists understand **how matter behaved during the first millionth of a second after the Big Bang** and provides clues about the **fundamental laws of QCD**.

So next time you see Sheldon shouting about "quark-gluon plasma", you'll know it's more than just a physics joke—it's a window into the **earliest moments of the universe**, revealing the **extreme conditions of matter**, and helping us decode the **deepest secrets of particle physics**.

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The 21cm Frontier

How Three-Dimensional Maps Will Resolve the Topology of Reionization

Pragun Nepal

The redshifted 21cm transition of neutral hydrogen offers three-dimensional tomography of cosmic dawn and the Epoch of Reionization. This feature article synthesizes simulation paradigms, statistical diagnostics and observational strategies that together aim to reconstruct not just the timing but the topology of reionization. I discuss how semi-analytic pipelines produce brightness-temperature cubes, why higher-order statistics (notably the bispectrum) are essential, and what remains to be done to translate mock signals into robust astrophysical constraints.

For decades cosmology's early chapters have been read from two-dimensional fossils: the cosmic microwave background and sparsely sampled high-redshift galaxies. The redshifted 21-centimetre line of neutral hydrogen promises something very different - three-dimensional maps of the intergalactic medium that record, in space and frequency, the thermal, ionization and density evolution of the first billion years. That prospect - and the practical work necessary to realize it - is the subject of this article.

The promise of a three-dimensional probe:

The 21cm line traces neutral hydrogen through a differential brightness temperature that depends on spin temperature, neutral fraction and local density. Because frequency maps directly to redshift, interferometers sensitive to metre wavelengths will produce volumetric datasets whose statistical and morphological content far exceed that of traditional surveys. This richness opens the possibility of measuring not only when reionization happened, but how ionized regions nucleated, grew, and connected into a percolating network.

From physics to mock observations:

Turning physical ingredients into realistic mock observations requires a deliberately engineered pipeline. The pragmatic and widely used route begins with N-body simulations that generate matter density fields across the redshift interval of interest; collapsed halos are extracted (for instance with Friends-of-Friends algorithms) and then passed to semi-analytic excursion-set radiative transfer modules that compute ionized fractions and the spin-temperature structure. The output - three-dimensional brightness-temperature cubes across many redshift frames - feeds a suite of diagnostics: power spectra, bispectra for multiple triangle shapes, and real-space topology measures.

Why higher-order statistics matter:

Bubble formation and merger are intrinsically non-Gaussian processes that induce phase correlations among Fourier modes. The bispectrum - the Fourier transform of the three-point correlation function - is sensitive to those correlations and to bubble morphology in a way the power spectrum is not. Different triangle configurations probe different aspects of the ionization topology: equilateral triangles are tuned to typical bubble sizes, squeezed triangles couple large-scale background modes to small-scale structure, and elongated triangles highlight anisotropic, filamentary signatures. Practical analyses of simulated HI maps find clear, redshift-dependent behavior in bispectrum amplitudes and signs; these trends provide direct morphological diagnostics complementary to the power spectrum.

What the simulations show:

Semi-analytic runs covering the epoch from cosmic dawn to the completion of reionization produce the expected progression: density and temperature fluctuations dominate early, small H II regions appear and grow, and later merge into extended ionized volumes. Power spectra display a characteristic turnover whose peak shifts to larger physical scales as typical bubble radii grow. Crucially, bispectrum diagnostics reveal additional structure: amplitude growth, configuration-dependent sign changes, and migrations of peak response that reflect percolation and topology transitions. These non-Gaussian signatures therefore act as proxies for the physical processes - source clustering, ionizing efficiency and X-ray heating - that drive reionization.

Practical obstacles and how to meet them:

The cosmological 21-cm signal is faint beneath bright astrophysical foregrounds and instrument systematics. Foregrounds are orders of magnitude larger than the signal; instrument chromaticity and calibration residuals leak foreground power into the same Fourier regions used to detect cosmology. To produce realistic detectability forecasts the mock-observation pipeline must fold in beam patterns, bandpass effects, foreground models, and thermal noise, and then test estimators under these corruptions. Light-cone effects - the evolution of the signal along the line of sight - further complicate estimators and must be included in forecasts. Tackling these challenges is largely an engineering exercise, but one that has profound consequences for whether higher-order statistics like the bispectrum are practically measurable.

Toward inference - statistics and machine learning:

Detection is only the first step. Extracting astrophysical constraints requires inference frameworks that can digest high-dimensional maps. Two complementary strategies are currently in play: (i) Bayesian forward modeling with fast, semi-analytic emulators that replace full radiative transfer in parameter sweeps; and (ii) likelihood-free methods (approximate Bayesian computation and neural density estimators) that learn mappings from summaries to parameters. Crucially, including bispectra and topology measures in the summary set breaks degeneracies that remain when using the power spectrum alone. Machine-learning surrogates trained on ensembles of simulations dramatically accelerate inference, but care must be taken that training sets span relevant systematic variations (foregrounds, beam errors, calibration uncertainties).

The road ahead:

The community should prioritize public, reproducible mock datasets and standardized analysis pipelines so instrument teams and theorists converge on common benchmarks. Efforts to hybridize semi-analytic speed with radiative-transfer fidelity will enable larger suites for inference. Statisticians must develop estimators for the bispectrum and topology that are robust under foreground marginalization. And observational programs should plan joint analyses that combine power spectra, bispectra and cross-correlations with galaxy surveys, thereby tightening constraints on source properties and heating histories.

Concluding perspective :

The 21-cm line is not merely another probe; it is a three-dimensional chronicle of the Universe's first luminous sources. To read that chronicle requires a synthesis of large-volume simulations, higher-order statistics, and careful instrument modeling. When the first detailed 21-cm maps of the early universe arrive, they will do more than set a date for reionization - they will reveal how structure, radiation and topology conspired to transform the cosmos from neutral to ionized.

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Sonoluminescence : Sound into Light

Rajat Chaudhary

Introduction

Figure 19: A standing sound wave with a frequency of 40,000 cycles per second generates 40,000 flashes of light per second that can be seen with the unaided eye. The blue/purple dots are the micron-sized spots formed in water by imploding bubbles. Courtesy : Photograph by Ed Kashi

During World War I, the race to detect submarines led to the development of SONAR technology and ultrasonic transducers. When the war ended, these transducers found their use in research labs, and scientists started testing ultrasound to enhance chemical reactions and speed up diffusion, since intense vibrations can mix solutions far more effectively than manual agitation. In 1933, Marinesco and Trillat and later Frenzel and Schultes tried to speed up the slow, diffusion limited development of photographic plates; they hoped that ultrasound would accelerate the penetration of developer into silver-halide emulsion. When researchers later developed photographic plates under ultrasound, they were startled to find faint exposures made in total darkness. What they observed was the exposure of faint flashes from collapsing cavitation bubbles – what we now call as “SONOLUMINESCENCE”. Many researchers studied this effect and carried out spectral measurements but were not able to draw any conclusions. These early experiments showed that collapsing bubbles could produce light but did not answer why. Since the bubbles forming in the fluid were countless and they gave off light in unpredictable and unsynchronized manner, it was difficult to understand the mechanism of emission of light.

Experiment and process

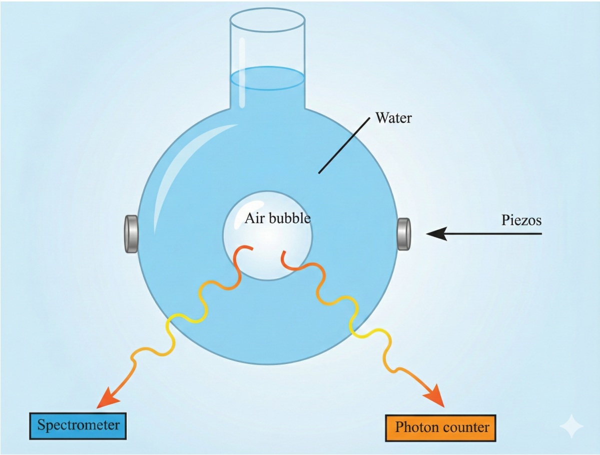

Figure 20: Sketch of a typical setup for generating sonoluminescing bubbles

A typical experimental setup for sonoluminescence included a glass flask filled with water and lined with ultrasonic transducers which are tuned to produce a standing sound wave at the resonant frequency of the jar. When the pressure amplitude Pa of the sound waves is larger than the normal atmospheric pressure P0 = 1 bar, the pressure at the rarefaction phase of ultrasonic wave becomes negative which puts the liquid under tension. When the tension increases liquid breaks apart and forms bubble clouds (cavitation) which are unstable and collapse with violence and do serious damage to the surface of nearby solid bodies.In 1989, Felipe Gaitan while working for his master’s thesis which involved searching for light emission from a single bubble (His advisor Larry Crum had seen hints of light emission from a single bubble in 1985) found out when a moderate forcing pressure (Pa $\approx$ 1.2 -1.4 bar) is applied and water degassed to 20%

of its usual dissolved air content is used, one can trap a single bubble with right acoustic conditions. It became easier to do experiments on a single bubble i.e. measuring its period of flashes and spectrum of light emitted and such, now researchers started looking for the mechanisms behind the glow. The phenomenon is divided into two groups, light emitted from an isolated single bubble trapped in a sound field is termed single bubble sonoluminescence (SBSL) while light emitted from the collapse of many bubbles forming in a liquid at the same time is termed multi-bubble sonoluminescence. Though they are the same basic phenomenon but they behave differently in emission and it is easy to study SBSL due to regular and predictable flashes in comparison to chaotic bubbles in MSBL. The theory of classical bubble dynamics was already developed by Lord Rayleigh (1917) while working on the problem of ship propellers being damaged by cavitation bubbles. The studies found that the motion of bubble during collapse closely followed Rayleigh's classical description.

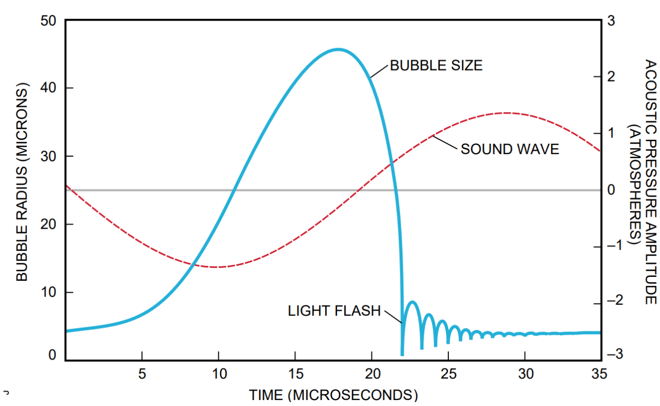

Figure 21: Radius R(t), driving pressure P(t) as observed in time. A negative driving pressure causes the bubble to expand; when the driving pressure changes sign, the bubble collapses, resulting in a short pulse of light, marked light flash.

When a single bubble in an ultrasonic sound field goes through a single cycle several physical processes occur in a sequence. The cycle starts when the pressure dips into negative half of the cycle, during this phase the bubble slowly expands from its normal radius (≈5µm) to its maximum (≈50µm). Since during expansion the pressure drops inside the bubble a large of water molecules evaporating from the wall and also some gas molecules enter inside. In this phase, the bubble is in both thermal and mass transfer equilibrium with the liquid. When the pressure becomes positive the expansion stops and the bubble's radius begins decreasing very quickly and water vapor condenses at the walls. The motion of collapse increases with decrease in radius of bubble. There comes a point when the motion becomes fast enough that the water molecules cannot escape. Also, at some point of time heat flow stops and then gas inside almost behaves adiabatically, which results rise in temperature as bubbles shrinks. As the collapsing bubble heats beyond roughly 4000 K, water molecules inside begin to break apart into reactive fragments like oxygen atoms and OH radicals. These chemical changes absorb energy and temporarily slow the temperature increase. At this stage, faint molecular band light emission is a possibility. During the early 1990's, experiments have shown that the sonoluminescence was sensitive to the type of gas within the bubble. Replacing dissolved air in water to pure nitrogen showed no sonoluminescence and similar was the case when a mixture of 80% nitrogen and 20% oxygen was used. Emission returned only when inert gases such as argon or xenon was added. The glow becomes strongest when only a tiny amount—around 1%—of argon or xenon is present, roughly matching their natural abundance in air. It is due to process at this stage that nitrogen and oxygen molecules tend to react and dissolve into the liquid during collapse, removing energy and thus leading to no light emission whereas inert gases do not react and remain trapped inside the bubble which causes more effective heating during collapse. As the bubble continue to collapse temperature kept on increasing despite limiting influence of water vapor. At around 10,000 K some of the Argon as well as Oxygen and Hydrogen atoms become ionized and release free electrons. These free electrons collide with ions and neutral atoms, releasing tiny flashes of radiation in the process—a plasma-like glow (thermal bremsstrahlung and radiative recombination). At the moment of minimum radius, the gas becomes extremely dense, and the collapse begins to lose energy through sound waves and instabilities in the bubble wall. The light emission reaches its peak here. During collapse, nearly all of the bubble's stored energy is shed, largely in the form of sharp acoustic pulses that ripple through the surrounding liquid.

After collapse, the bubble begins to expand, much slower than the compression. The temperature drops sharply, the chemical reactions stop, and the interior begins to return to equilibrium. Finally, The bubble rebounds to a much smaller size than the maximum radius before the main collapse. These after-bounces are too weak to produce light. The radial motion is, however, damped rapidly until the driving pressure dips into its negative cycle once again, and the oscillation starts anew. Over the whole cycle, the bubble may get net gain or loss of gases and even some shape deformation and this could stop the further cycles. But for correct parameters range the process repeats itself with stability and continues to emit light in periodic fashion.

Unsolved problems and mysteries

The above explanation describes the basic picture of how the bubble grows, collapse and emits light, but this simple model is based on approximations and leaves out many details. More advanced numerical simulations and experiments have shown that additional effects may play a role inside the bubble. Early theoretical work by Moss and co-workers (1997) predicted that a violent inward-moving shock wave forms during collapse and could raise the bubble's interior temperature to nearly 10^6 K. However, later simulations by Yuan and Feng (1998), Vuong and Szeri (1996), and Storey and Szeri (2000) showed no clear formation of shocks under typical SBSL conditions. Some studies, such as those by Xu and colleagues, suggested that shock waves may appear only in specific situations—for example, in xenon-filled bubbles with more than 30% water vapor. The amount of water vapor trapped inside bubble at maximum compression is crucial for the problem of maximum bubble temperature. But detailed models of water vapor chemistry in the bubble have several uncertainties in the reaction rates for even fundamental processes, as the peculiar condition inside the bubble have not been probed in the experimental setups. Therefore, temperature predicted from these reactions is uncertain. Experimental measurements by Hiller et al. (1992) showed that the emission spectrum of SBSL could be fitted by a smooth blackbody-like curve, suggesting temperatures between 10,000 K and 20,000 K. But because the bubble is extremely small and optically thin, it cannot behave like a true blackbody radiator, even if its spectrum resembles one. Plasma-based models developed by Hilgenfeldt, Brenner, and Lohse—which include electron–ion bremsstrahlung and radiative recombination—match the observed spectra for similar temperatures and are currently the most widely accepted explanation. At the same time, some simulations by Storey and Szeri predict temperatures closer to 7000 K, while other models (for example, those by Barber and Putterman) have suggested that using multi-frequency driving could push temperatures toward 10^6 K even in the absence of a shock wave. Moss et.al suggested possible existence of two temperatures for ions and electrons as the collision rate of the atoms may not be sufficient to thermalize the electrons. Exact temperature and its dependence on experimental factors is still disputed. In 2002, a research group led by Taleyarkhan claimed that collapsing bubbles in deuterated acetone were producing tell-tale signs of nuclear reactions, such as neutrons and traces of tritium. They claimed temperatures of 106-107 K via shock focusing sufficient for fusion. But subsequent independent tests by Shapira and Saltmarsh and later by other laboratories found no neutron emission correlated with sonoluminescence. Since the shock-wave formation is still unresolved, so is the question of bubble fusion. Researchers have done studies on the role of molecular emission in sonoluminescence. Flint and Suslick (1989) observed emission lines from excited CN molecules in the spectra of SBSL in organic liquids such as methylformamide and adiponitrile. Faint emission bands from excited OH radicals have also been observed with long exposure time (5 days) in extremely dim SBSL when bubble is driven using low acoustic amplitude wave. Yet most theoretical models predict that the extremely high densities reached during a single-bubble collapse should strongly suppress such molecular features, making them nearly invisible. In multi-bubble systems (MSBL), NaCl solutions show strong sodium emission lines around 589 nm, while single-bubble sonoluminescence shows no such lines. It is still unclear whether these emissions come from gas-phase atoms inside the bubble or from chemical reactions occurring in the surrounding liquid (termed as chemiluminescence). Both processes have experimental support, and the exact contribution of plasma vs chemical emission remains unresolved.

Applications and future

The SBSL is highly robust and promise technological applications in various disciplines. In SBSL experiment light is emitted with highly stable periodicity. Measurements have shown that the timing of the light flashes is stable to about five parts in 10^{11}, even without any attempt to optimize the setup. A cheap precision frequency source may be developed in labs using SBSL setups. Sonoluminescence involves enormous energy concentration created during collapse of bubble. This energy is used to influence chemical reactions in MSBL setup, use of ultrasound to enhance, assist, or induce chemical reactions that would not occur spontaneously is termed as sonochemistry. Bubbles and cavitation are required for sonochemistry but it is not clear at all where exactly the chemical reactions take place: in the interior of a collapsing bubble, at their surface, in a liquid layer around the bubble, or even at greater distances, mediated by the diffusion of primary reaction products from the bubble interior. E.g. In the conventional reactor process of reducing potassium iodide to iodine takes hours, when ultrasound is used at a frequency of 20kHz reaction time is reduced to few minutes. Amorphous iron-used as catalyst- is difficult to produce by conventional cooling of molten metal, because crystallization occurs too quickly. Ultrasound can fragment molten iron into microscopic droplets that cool so rapidly in the surrounding liquid that they solidify before forming crystals, enabling the production of amorphous iron. As research tools have improved, new experimental strategies have expanded the ways sonoluminescence can be investigated. Ultrafast spectrometers and streak cameras now capture the picosecond-scale timing and spectrum of each flash. Experiments in cryogenic liquids, ionic liquids, and metal-containing solutions have begun investigating how far the phenomenon can be pushed beyond water, and machine-learning techniques allow precise tracking of bubble shape and stability. Future work may also extend into exploring deeper ultraviolet and infrared emission—regions that remain difficult to access due to strong absorption in most liquids. There is similar interest in achieving controlled sonoluminescence in high–surface-tension liquids—some theoretical models predict that liquids with very high surface tension—such as mercury—could support far more intense collapses, though this remains untested due to practical and safety challenges. Together, these developments indicate that despite a century of study, many aspects of sonoluminescence remain open to exploration.

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Is It All Just Music?

The Symphony of String Theory

Soham Kulkarni

Introduction

The great minds of the physics community have gifted us two masterpieces: general relativity and quantum mechanics. General relativity governs the movement of massive stars and black holes, while quantum mechanics rules the subatomic realm. But to the dismay of physicists, these two great pillars of physics crumble when both the massive and microscopic nature of the singularity at the centre of a black hole come into the picture. The equations of general relativity and quantum mechanics, when combined, echo nonsense infinities. This incompatibility is the largest obstacle in our quest to find the "Theory of Everything."

The most radical solution to this decades-old crisis is string theory, the most promising and mathematically consistent theory physics has come up with so far. It not only resolves the compatibility issues between relativity and quantum mechanics but also provides new and exciting insights into the nature of our universe and the fundamental reality itself.

An Overview of the Standard Model

The Greeks imagined "atomos," the uncuttable seed of reality. In fact, the word "atom" is derived from exactly this Greek word. But the particles we call atoms aren't uncuttable; they consist of electrons, protons, and neutrons, which are further made of even smaller particles called quarks. But there were other fundamental particles discovered too, those which do not make up any objects we encounter in our daily life, but they exist, are used in, and are produced from various nuclear reactions. One such particle is the ghostly neutrino, which barely interacts with matter. Heavier versions of these particles have also been detected by the Large Hadron Collider at CERN.

Table 1 classifies these particles into three families. Each particle in the table below has an antiparticle counterpart. Matter and antimatter, when in close proximity, annihilate each other into pure energy, i.e., light. Antimatter possesses the same properties as its matter counterparts, like mass and lifetimes, but differs by having an opposite charge.

Table 1: The Three Families of Matter Particles

QUARKS		
Family 1	**Family 2**	**Family 3**
Up quark	Charm quark	Top quark
Down quark	Strange quark	Bottom quark
LEPTONS		
Family 1	**Family 2**	**Family 3**
Electron	Muon	Tau
Electron neutrino	Muon neutrino	Tau neutrino

These particles interact via the four fundamental forces in our universe, each of which has a particle associated with it. These particles represent the smallest "bundle" or "packet" of the force. The gluon and the weak bosons are associated with the strong and weak nuclear forces, respectively. The photon represents the smallest packet of electromagnetic force, while the hypothetical graviton is the particle of the gravitational force.

The Higgs boson deserves a special mention, which is the particle responsible for giving mass to all the other particles. All these particles constitute the Standard Model of Particle Physics. The major drawback of this model is that it explains the interactions of these particles with one another and all their properties with great accuracy but doesn't explain the origin of these particles. It fails to answer the question "why?" Why are there only three families of matter particles? Why is the gravitational force so many orders of magnitude weaker than the other forces? Why are there only four fundamental forces? Another major pitfall is that we haven't been able to detect the graviton yet. Finding the smallest bundle of the weakest force of the universe presents quite a challenge to experimental physicists.

To overcome the hurdles presented by our old theories, string theory comes to our aid. String theory suggests that each particle mentioned in the Standard Model isn't the fundamental unit in our universe; in fact, each of those particles is made by a tiny one-dimensional closed loop. By the end of this article, it will be clear how abandoning the point-particle approach resolves so many previously unanswered questions. To understand string theory, however, we must first gain a basic understanding of Einstein's relativity and quantum mechanics.

Special Theory of Relativity

During the 19th century, Maxwell was gaining popularity due to his famous four equations that combined electricity and magnetism. A shocking corollary to these equations was the fact that the speed of light was constant, regardless of any reference frame, and this was experimentally verified. This directly contradicts Newtonian mechanics and our intuition of relative speeds adding up. Was our physics completely wrong, or was a critical piece of information missing? Einstein found this aspect of light difficult to comprehend. The special theory of relativity was the result of resolving this crucial problem. It states that a direct consequence of the constancy of the speed of light is this: as an object gains speed, the passage of time slows down for that object. Also, its length contracts in the direction of motion. These effects are called time dilation and Lorentz contraction, respectively. These effects only become noticeable at speeds that are substantial fractions of the speed of light, which explains why they are such a rare sight.

Einstein realized that these bizarre effects were only plausible if space and time were woven into a single flexible fabric: spacetime. Special relativity states that every object moves through spacetime at a constant speed, the speed of light. When an object is stationary, it moves fastest in the dimension of time, thus aging the quickest, while moving objects have their speed distributed throughout the 4 dimensions. This is the reason for time dilation. This results in another surprising fact: nothing can move faster than light. Einstein's famous equation $E = mc^2$ tells us that energy and mass are interconvertible. It can be mathematically demonstrated that accelerating a massive particle to the speed of light requires infinite energy. The speed of light can only be attained by massless particles.

General Theory of Relativity

Newton's theory of gravity was incomplete as it had two major flaws. While it predicted the exact mechanism of gravitational force, the theory failed to explain its origin, or what exactly gravity is and how two bodies millions of kilometres away can, in any way, affect each other. Additionally, his theory required gravity to act instantaneously, which didn't align with the universal speed limit established by special relativity. A new framework was needed to explain these complications. So Einstein set out to rebuild our understanding of gravity from the ground up.

Just as motion in free space cannot be distinguished from being stationary without external forces, it is also impossible to distinguish between the effects of gravity and accelerated motion. So if gravity and accelerated motion are indistinguishable, gravity must not be a traditional force. It must be a property of space itself.

Another revolutionary postulate of Einstein was the warping of spacetime due to mass. To gain a visual understanding of this concept, imagine a bowling ball on a stretched, thin rubber membrane. The membrane is distorted under the weight of the ball. The only difference is that, instead of some "sheet" changing its shape, the very fabric of reality is distorted due to the mass. The greater the mass, the more intense the distortion of spacetime. It was experimentally verified by observing the bending of light around the sun coming from distant stars.

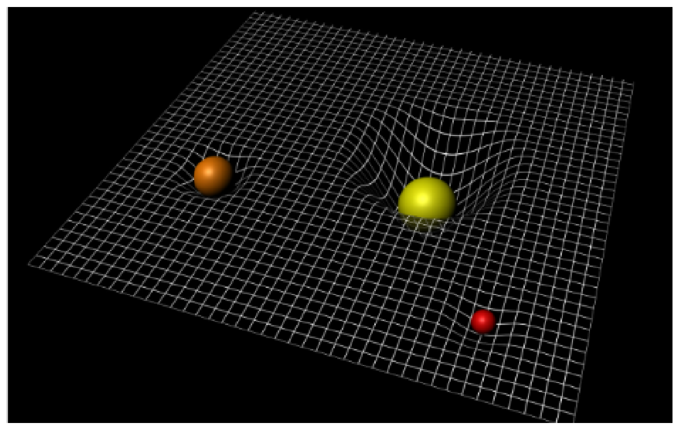

Figure 22: Warping of spacetime by a massive object

This is our answer to the question, "What is gravity?" It is the warping of spacetime. And these disturbances travel at the speed of light and affect other objects. Though general relativity elegantly fills the gap in Newton's theory of gravity, its equations dissolve into meaningless infinities at infinitely dense singularities at the centre of black holes. To understand the physics at such extreme points, a theory of quantum gravity was needed. So now, we turn our heads to the beautiful, mysterious, and puzzling theory of quantum mechanics.

The Quantum Realm

In the early 20th century, a thought experiment perplexed physicists worldwide. If a finite region of vacuum is heated, what will be the energy inside it? In a vacuum, heat is transferred by radiation, i.e., electromagnetic waves. Electromagnetic waves carry energy, but when physicists tried to calculate the energy due to these waves in a finite region, it turned out to be infinity. This was the infamous ultraviolet catastrophe. Thus, once again, physics screamed for a new perspective. A radical approach was therefore taken, considering energy as discrete bundles rather than a continuous quantity. This minimum energy, or "bundle," was directly proportional to the frequency of the electromagnetic wave, and this bundle is none other than the photon. So is light a wave or a particle? The answer is both! As revolting as this idea might be, we must bear in mind that the physics we experience around us is just a special case of quantum mechanics. The subatomic world holds many unexpected ideas that seem counterintuitive, yet they are the reality.

De Broglie then had a crazy idea: what if, like light, matter also possessed such a dual nature? Later, it was confirmed through experimentation that an electron has wave-like characteristics. These waves are probability waves. The wave equations tell us the probability of finding the particle at a particular location, but one can never be 100% sure. Despite the dissatisfaction of many scientists, the non-deterministic nature of QM was finally accepted.

A surprising result of this probabilistic approach is the uncertainty principle. It states that one can never measure the position and momentum of a particle simultaneously exactly; there will always be some error in the measurement, not due to the limitations of our instruments, but because it is a fundamental property of subatomic particles.

Now it moderately makes sense why a probabilistic theory like QM cannot elegantly merge with the smooth, deterministic geometry of general relativity. What exact problems occurred when the equations of such powerful theories were used together?

The Problem

The incompatibility between relativity and quantum mechanics is a fundamental paradox in our description of reality. Quantum field theory (QFT) is a framework that attempts to unite quantum mechanics and the fundamental forces. Sadly, uniting gravity and QM proved to be a tough task. The reason is this: QFT states that empty space isn't empty, it is seething with quantum fluctuations. Virtual particles are popping in and out of existence, their brief existence allowed by the energy-time uncertainty principle.

General relativity describes gravity as smooth and deterministic. Absence of mass implies a calm and flat space. Fluctuations in the gravitational field mean fluctuations in mass-energy (by $E = mc^2$). General relativity lacks the mathematics for such a probabilistic gravity. This conflict turns catastrophic at the Planck length (10^{-35} meters). The math explodes, spewing the same infinities as those found at black hole centres. The two theories are not merely difficult to combine; the core of these theories is fundamentally dissimilar. This fundamental flaw was the gap that string theory was conceived to bridge.

String Theory

To resolve the conflict between relativity and quantum mechanics, physicists had to make a radical sacrifice: discarding the point-particle approach. What if quantum physics were an approximation and particles weren't points but one-dimensional looped strings? This simple change in perception brought about the greatest and most ambitious revolution in theoretical physics.

The standard model required 19 parameters to be used as input in the equations, which accurately predicted every particle interaction ever observed. However, it failed to explain why the values of these parameters are as they are. String theory requires only one parameter that explains every one of these 19 parameters.

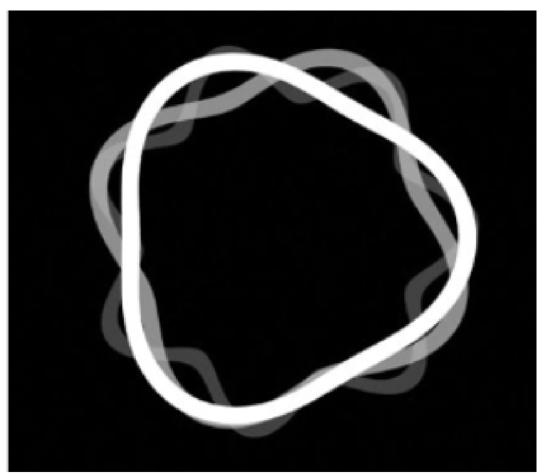

Figure 23: Vibrating strings as fundamental particles

The notion of a string is exactly what one might think: a one-dimensional, thin filament. And just like the strings on a guitar, these strings vibrate with different frequencies. Since they are closed loops, they form standing waves.

The critical idea is that every known particle is composed of the same type of string. It is the different frequency of vibration that gives rise to different particles. Therefore, more frantic vibrations correspond to more energy and, consequently, mass. So there exists a direct association between the vibrational pattern and a particle's mass.

Strings have extremely high tension, which causes them to shrink down to extremely small lengths of the order of 10^{-35} meters (Planck length). The parameter that determines the characteristics of particles is precisely this tension. For example, the force transmitted by gravitons was found to be inversely proportional to tension in strings, which explains why gravity is far weaker than the other three forces.

But how does string theory resolve the conflict between relativity and quantum mechanics? Discarding the point-particle approach and accepting strings as the most fundamental unit in our universe has a remarkable effect: distances smaller than the Planck length can have no effect on strings and anything consisting of strings.

To determine the structure of smaller particles, we use probe particles, like photons or electrons. Quantum mechanics states that increasing the energy of these probes enhances their capability of penetrating structures and helps us discover smaller and smaller particles. But this is not true for strings. Mathematically, it was shown that increasing a string's energy initially enhances its probing ability, but after a certain point, the string's length starts to increase. Even the most fundamental structure of the universe cannot be used to probe sub-Planckian lengths! String theory teaches us that there is a limit on how far we can zoom into space. The idea of lengths smaller than the Planck length holds no meaning. Recall that the violent undulations of spacetime, as a consequence of quantum mechanics, occurred at scales smaller than the Planck length. So there is no way that these fluctuations, in any way, affect strings and anything consisting of strings.

The solution to tame these fluctuations might dissatisfy some of the readers. But we have actually solved the problem, not just ignored it. Because we believed that particles were zero-dimensional points, relativity and quantum mechanics were incompatible. By simply considering particles as one-dimensional strings, the concept of sub-Planckian lengths becomes illogical. The idea of rejecting the point particle approach was proposed by many physicists, including Dirac, Pauli, and Feynman. But any such theory created violated one or many basic principles of the universe, like conservation of energy, conservation of quantum mechanical probability, or constancy of speed of light. The wonderful feature of string theory is that it not only accepts these facts, but it is also a necessity for the mathematics to be right.

Doors to Different Dimensions

In 1919, Theodore Kaluza had a wild idea. What if our universe had five dimensions instead of four? When he applied this idea to Einstein's equations of relativity and reformulated them, he found something remarkable. These new equations were none other than Maxwell's equations. He had united two forces, gravity and electromagnetism, that were previously thought to be unrelated.

Unfortunately, the mass and charge of the electron predicted by these equations deviated from experimental values, consigning Kaluza's elegant idea to a historical footnote until string theory resurrected this idea.

As string theory mended the infinite probabilities appearing in the equations of general relativity, a new problem arose. Some systems yielded negative probabilities, which is nonsensical since probability ranges from 0 to 1. Another strike against our intuition and observations was made when it was found that these negative probabilities vanished when our universe was considered as a ten-dimensional space (nine spatial and one temporal dimension).

To gain a visual insight into this absurd idea, think of a stuntman at a circus, walking on a taut rope. He has only one direction he can walk in: the front-back direction. But on the same rope, a tiny ant has an extra direction it can move in, i.e., around the rope.

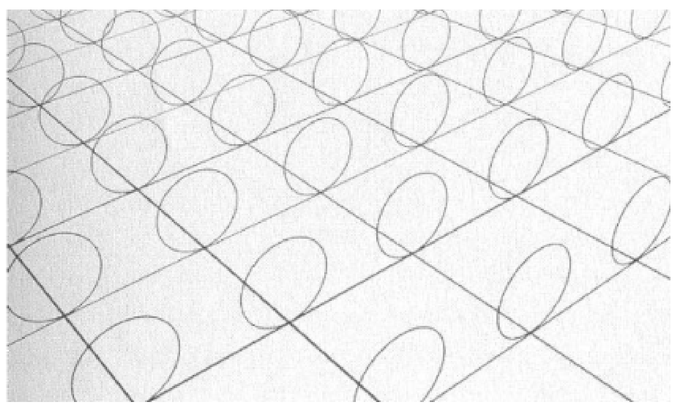

Figure 24: Visualizing extra dimensions

This set off the idea that maybe these extra dimensions that balance our equations are not visible to us because they are so tiny they seem invisible, or rather, non-existent.

The flat space in the image represents the 3D space we experience, while the circles represent a new, tiny dimension invisible to the naked eye.

However, string theory predicts six extra dimensions, curled up upon themselves in a complex manner. How do we find such a shape?

The answer to this is provided by Calabi-Yau manifolds. A Calabi-Yau manifold is a six-dimensional space. The geometry of such a space is determined by intricate mathematics.

But such a crumpled hyperspace cannot take any shape; the equations of string theory restrict the geometrical form it can take. One example of such a space is given in the images below. The vibrational pattern of a string is heavily influenced by its shape, as the string gains extra degrees of freedom, allowing it to vibrate in independent directions.

In essence, the hidden geometry of the Calabi-Yau manifolds encodes the very laws of physics we observe around us.

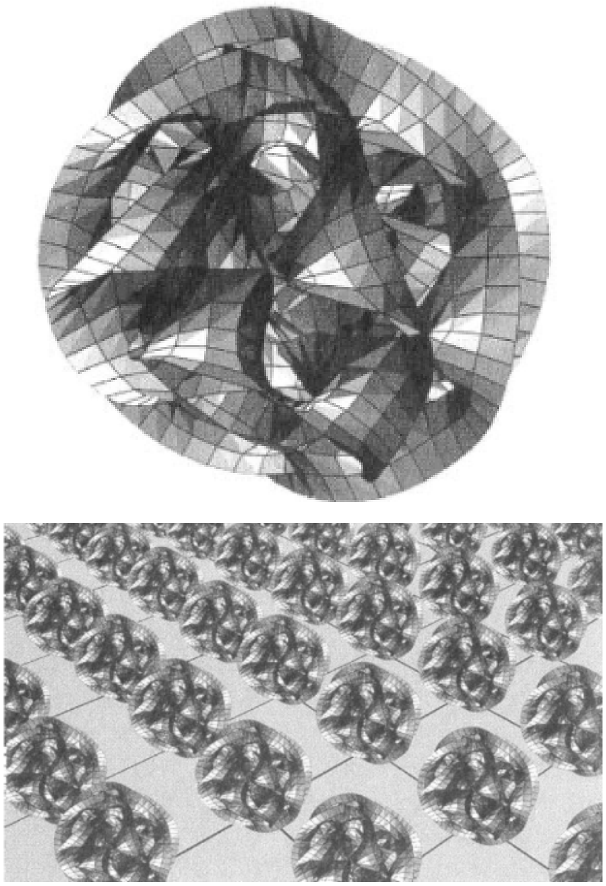

Figure 25: Calabi-Yau Manifold

But do the properties emerging from the theory agree with the experimental data?

State of String Theory

The biggest drawback of string theory is its inability to make testable predictions. The mathematics behind string theory is so complex and advanced that it is still being figured out to this date. The equations of string theory are approximate, and the tools to extract the exact equations are currently not to be found. String theory in our hands in this age is equivalent to people in the 1700s having access to today's supercomputers. We simply lack the technology to verify such a colossal claim.

As Glashow comments, "String theory is so ambitious that it can only be totally right or totally wrong. The only problem is that the mathematics is so new and difficult that we won't know which for decades to come."

While the particles and their properties arise from the vibrational pattern of strings, the strings themselves can vibrate in an infinite number of patterns, predicting an infinite tower of particles (Regge trajectory). But the masses of such particles are so large, the energy to discover these particles is a million billion times greater than what today's particle accelerators have achieved.

The Landscape Problem: Even though the geometry of the curled-up dimension is restricted, the number of possible solutions is greater than 10^{500}. Finding the appropriate shape of a Calabi-Yau manifold that theoretically predicts the properties of particles we experimentally calculated will require a Herculean effort. Many scientists, after examining the landscape, were disappointed by the sheer scale of the problem. Years of research later, some physicists concluded that each and every possible configuration of the manifold was on an equal footing. All these configurations exist simultaneously, suggesting the existence of a multiverse. Unlike the many-worlds interpretation of quantum mechanics, the string theory landscape predicts universes with fundamentally different laws of physics. Our universe is just one among those that allow for the formation of stars, planets, and ultimately, us.

But all of this only lies in the realm of exquisite theory. The elegance of string theory is perfectly rivalled by our technological limit. For the first time in the history of physics, experimentalists have lagged far behind theorists. Yet, the search continues, not just for the missing piece, but for the very loom on which the beautiful tapestry of reality might be woven. Whether string theory is the final story or just a brilliant stepping stone, it has undoubtedly expanded our vision of what the universe can really be, an elaborate orchestra, conducted by the intricate notes of cosmic dancing bands.

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