THE STARRY MESSENGER

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"The 3-Body Problem—Is it Unsolvable?" by Kajol Mistry

"Where Did Mars' Atmosphere Go?" by Sherlyn Nammi

"Hiding in the Numbers—What Does Quantum Mechanics Say About the Reality of Electromagnetic Potential?" by El Ducluzeau

"On Gauge Theory" - Research Report by Quantum Mechanics alumni

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We are thrilled to bring you the second edition of *The Starry Messenger*, the triannual science magazine of the Global Society of Young Physicists (GSYP). This issue introduces the extraordinary work of physicists worldwide, featuring three remarkable research articles and one insightful report that explore cutting-edge topics in modern physics:

- **The 3-Body Problem—Is it Unsolvable?**
- **Where Did Mars' Atmosphere Go?**
- **Hiding in the Numbers—What Does Quantum Mechanics Say About the Reality of Electromagnetic Potential?**
- **Gauge Theory**

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The 3-Body Problem - Is it Unsolvable?

Author: Kajol Mistry

Physics' 3-body problem hit mainstream media with the 2024 American television series '3 Body Problem'.

In this article, Kajol Mistry, a student of Theoretical Physics at King's College London, explores possible solutions to the seemingly-unsolvable 3-body problem.

In 2024, a Sci-Fi Netflix show took the world by storm—that is, of course '3 Body Problem', based on the book trilogy by Cixin Liu; I must admit that I haven't seen the show nor read the books, yet the 3-body problem has been fascinating to me for some time. Many mathematicians and physicists have also found it fascinating, spending years dedicated to this problem—these include Newton, Poincare, Euler, Lagrange, Jacobi and many more. But what is the 3-body problem, and why is it so fascinating? In short, the 3-body problem is a specific case of the n-body problem and is seemingly unsolvable. Yet, models of the 3-body system have been made, so how have scientists been able to do this?

Let us first consider an n-body problem [1]. The n-body problem wants to model the movement of a system of n objects (bodies) due to the gravitational forces between them. If n=1, we can use the example, the Earth orbiting the Sun. We treat the Sun as stationary, and so we can solve the motion of the Earth simply using circular motion. If n=2, we have the two-body system, like a binary star system — this problem can be solved using a system of coupled differential equations. The next step would be the n=3 case, which would model systems like the Earth, Sun and Moon. This, however, has been very complicated to deal with. The orbits of the three bodies are random and chaotic, and simulations of such systems have shown that the initial conditions (like positions of the bodies relative to each other) can have huge effects on the progression of the system; these simulations also show that very often, one body (the one with the smallest mass) will be expelled from the system, leaving behind a two-body problem. Newton wrote about the 3-body problem in his book, *'Principia'*, and stated that it was impossible; yet, for centuries researchers have worked on this problem, and some solutions have been found.

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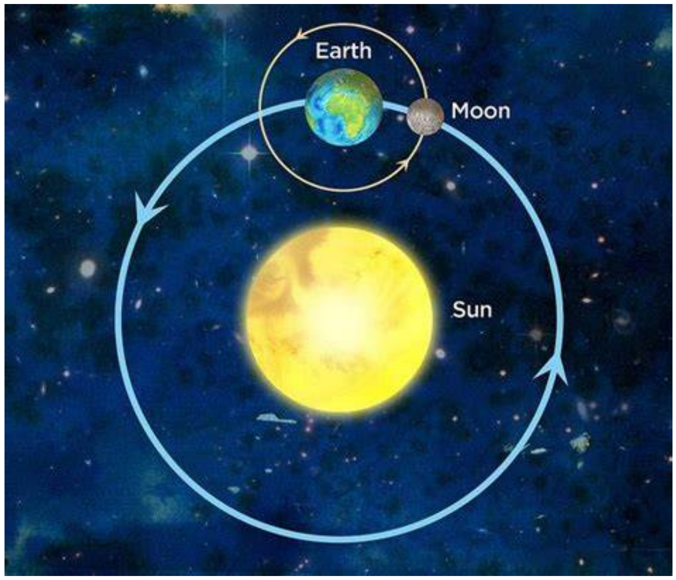

A model illustrating the 3-body system of the Earth, Sun, Moon, which physicists such as Newton have long thought is an impossible n-body problem.

There are some cases where an approximation can be used to model a 3-body system. A 3-body system may be broken down into separate 2-body systems if the distances between the bodies are large [2]. Take the system of the Sun, Jupiter and Saturn, for example—this can be split such that Jupiter and its orbit of the Sun is one 2-body system, and Saturn and its orbit of the Sun is another 2-body system. These can be solved as separate systems, but they will not be entirely accurate, as the effect Saturn and Jupiter have on each other have been ignored—so this method can only be an approximation. Another approximation, known as the 'Reduced 3-Body Problem' [3], can be made if one of the three bodies has a much lower mass compared to the other two bodies. The Sun, Earth and a satellite orbiting the Earth would be a system where this is applicable, as the mass of the satellite is so much lower than that of the Earth and Sun and so its gravitational effect is negligible by comparison. We can therefore assume it moves within the 2-body system of the larger objects (in our example, the Sun and Earth).

Earlier, we stated that the initial conditions have huge effects on the progression of the 3-body system, so does that mean that for specific initial configurations we can solve the 3-body problem? Well yes, we have analytic solutions for two very specialised sets of conditions [4]. Euler discovered that for three bodies orbiting a much larger centre of mass, there are solutions, given that they orbit in a straight line—like an eclipse (but they

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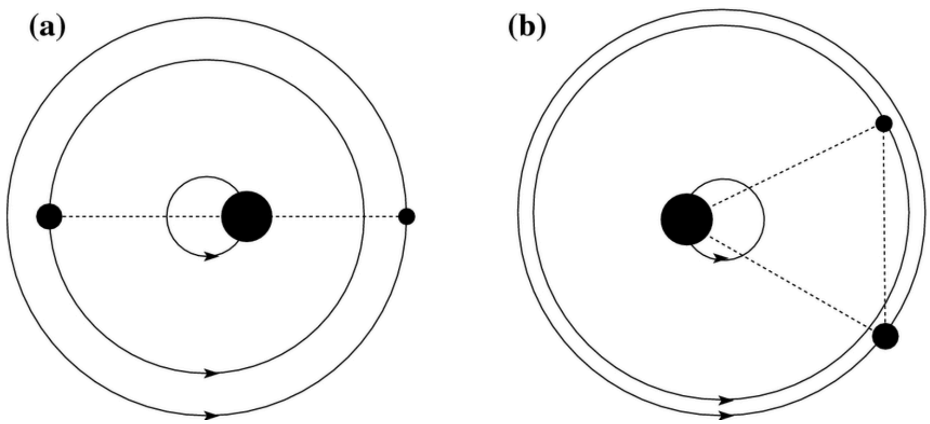
remain in this formation throughout their orbit). Lagrange discovered that, for two bodies orbiting a mass, if the bodies are equidistant (they form an equilateral triangle shape), then we can find solutions to the system. These systems can both be solved with relatively simple equations; thus, these specific points are known as the Lagrange Points [5]. If you placed a relatively low mass object at any of these five points, they would orbit indefinitely. These points are very important for space exploration—for spacecraft trajectories and artificial satellites.



The left diagram (a) depicts Euler's solution to the 3-body problem, while the right diagram (b) depicts Lagrange's solution.

The use of computers and numerical simulations has meant that more solutions to the 3-body problem have been found in recent years, specifically periodic 3-body systems, where the bodies will return to their original configuration. Moore numerically discovered a stable orbit of a 3-body system, in the figure 8 shape, which was mathematically proven by Chenciner and Montgomery [7]; this discovery then led to many more periodic solutions of the 3-body problem. These solutions are full of complex algebra and equations, but Montgomery came up with a way to visualise the system: the Shape Sphere [2]. Imagine each body to be a vertex of a triangle. The centre of the triangle is the centre of mass of the system and therefore fixed, and the shape of the triangle will change as the system progresses. Discarding information like the orientation and size of the triangle, we then map these vertices to the surface of a sphere, and we can see some solutions appear: our vertices being along the equator of the sphere (in a straight line)

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represents Euler's solution; similarly, our vertices being at the poles represents Lagrange's solution; many other solutions to periodic 3-body systems can also be seen using the Shape Sphere. Modern technology, including supercomputers, has led to many more solutions being found—there now exists approximately 12,000 solutions [8]. However, 3-body systems tend to eject one body after enough time, so these 3-body systems (beside the Euler and Lagrange solutions) are very unlikely to appear naturally.

We now know that solutions to the 3-body problem exist, approximately 12,000 of them! But why do we still deem the 3-body problem to be unsolvable? Well, the 12,000 solutions that have been found model systems, which, for the most part, do not appear in nature, deeming them effectively useless for many physicists. And the 3-body systems that appear in nature have been solved through approximations. Additionally, the lack of a general solution seems to be the reason we do not consider this problem solvable; yet a general solution was found in the form of a convergent, infinite series by Karl Sundman, but it takes around $10^{8,000,000}$ terms before it converges [2], which is an incredible amount of terms—altogether making this solution not very useful either. Therefore, to consider this problem solvable, we require models that describe systems that occur in nature and are reasonably solvable.

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Where Did Mars' Atmosphere Go?

Author: Sherlyn Nammi

The fourth planet in our solar system and our sister planet Mars has little to no atmosphere today. However research has shown that this was not always the case.

In this article, Sherlyn Nammi, a student of Physics with Astrophysics & Cosmology at King's College London, explores the events that led to the mysterious disappearance of Mars' atmosphere and why those events came to be.

The red planet that we know of hosts a weak and thin atmosphere with a pressure only 0.6% that of Earth's, but it was not always this way. Aeons ago, Mars had a thick atmosphere much like the current Earth—one that supported vast oceans of liquid water. So what happened for it to change so drastically?

In 2012, NASA's Curiosity rover took soil samples from an area of Mars' Gale Crater. A chemical analysis showed that although the surface of the planet appears to be completely dry, remarkably, roughly 2% of its soil contains water [1]. This, along with the planet's massive geographical formations that could only be formed by running water, provide ample evidence as to how wet the planet was in the past.

From the collected research, we understand that around 4 billion years ago, Mars was a water-rich planet. It persisted this way for hundreds of millions of years during a phase of its history known as the Noachian period. It had vast seas that spanned its Northern hemisphere, running rivers and lakes, and its atmospheric pressure rivalled that of Earth's or may have been even greater. However, all this disappeared within the span of just a billion years.

It is hard to deduce what happened to the surface of the Earth in the past due to its rapidly changing state, but this is not true for our nearest celestial neighbour. The moon's surface is littered with craters and impacts and has remained virtually unchanged for aeons, allowing us to take a peek into the events of the earlier solar system. Isotopic dating of lunar rock samples brought back by the Apollo astronauts showed us something quite strange. The analysis showed that a large portion of impact melts occurred in a very short period of time [2]. This was the evidence of a violent period of our solar system's history that affected the terrestrial planets like Earth and Mars.

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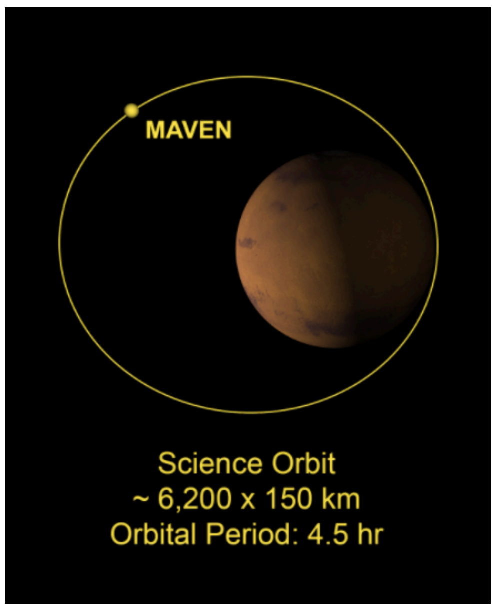
Mars was subjected to a devastating barrage of asteroid impacts in a time known as the late heavy bombardment. The disproportionate number of impacts is thought to have destroyed a third of its surface, drawing an abrupt close to the Noachian period.

It had entered a rigid, arid era known as the Hesperian. All of the planet's water was turned into giant blocks of ice, and it simultaneously became far more volcanically active. The bombardment had left its mark but what happened for Mars to change so drastically and for Earth to remain a flourishing world?

In 2013, NASA's MAVEN (Mars Atmosphere and Volatile EvolutioN) orbiter launched with the mission of surveying the remains of Mars' atmosphere to possibly find a cause for the planet's dramatic change.

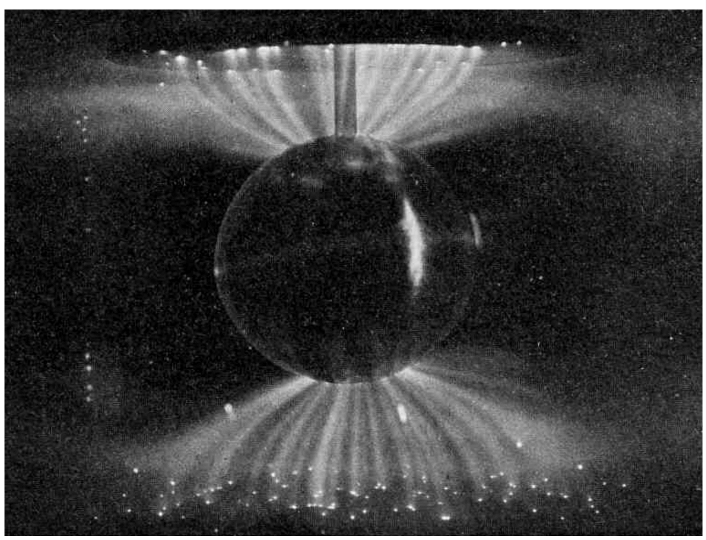


MAVEN's orbit around Mars as of February 2019, with a highest altitude of 6200km and an orbital period of ~4.5 hours. [3]

Equipped with eight sensors designed to survey the behaviour of atmospheric particles, MAVEN traced elliptical orbits around the planet to fully profile even the highest layers of the upper atmosphere. It was in doing this that a major clue to solving the mystery of the disappearance was found.

MAVEN found that gas is being lost from Mars' atmosphere and dissipating into space at a rate of about 2 kilograms every second [4]. It was this stripping of the gas that over time did away with Mars' insulating layer. But what was causing this phenomenon in the first place?

The answer lies in an unexpected area: the corona. The surface of the sun remains at a temperature of around 6000 Kelvins, but its surrounding layer, its corona, can reach millions of degrees Celsius. It is a violently flowing layer of plasma that spans millions of kilometres into space. These electrically charged particles occasionally gain so much energy that they can escape the coronal layer and blast through space at hundreds of kilometres per second, forming solar winds that are capable of stripping away planetary atmospheres—a process known as sputtering. Earth is constantly subjected to these violent outbursts but our atmosphere somehow remains safe. This is all attributed to the invisible shield that constantly protects us from the dangers of outer space—our magnetic field. It surrounds the Earth and deflects the barrage of solar winds, causing the electric particles to flow around and past us in a region known as the magnetosphere.



A laboratory simulation of the influence of the magnetosphere on solar winds- created using Birkeland currents in a terrella. [5]

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In electrodynamics, magnetic fields are produced by moving currents of charge. Likewise in planets, they are made by churning convection currents of molten liquids in their cores which conduct electricity and carry electrical charge—acting essentially like a dynamo and creating the magnetic field.

In the early stages of our solar system, Mars was created in a region with considerably less rocky material in comparison to the Earth, and formed with around half its diameter. The difference in size meant that Mars' core had cooled a lot more quickly, leading to its internal dynamo switching off and leaving it vulnerable to the onslaughts from space. The solar winds were made free to tear away at its atmosphere over the millennia.

These events were ultimately what led to the disappearance of Mars' once-thick atmosphere. The absence of such a valuable factor in sustaining life is a challenge that scientists face when pursuing the goal of eventually making a habitable region on the red planet. Habitats would have to be sealed away from the thin atmosphere of primarily carbon dioxide, and in doing this, would allow us to hopefully step foot on the red planet within the next decade.

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Hiding in the Numbers
—What Does Quantum Mechanics Say About the Reality of Electromagnetic Potential?

Author: El Ducluzeau

Electromagnetism describes the various interactions between charged objects and the invisible electric and magnetic fields that permeate space. When calculating these interactions, scientists can simplify the equations involved by using a tool known as 'potentials', which are alternate ways of representing the fields in question. Though they are useful, they are considered purely mathematical objects with no physical meaning.

In this article, El Ducluzeau, a student of Physics with Astrophysics & Cosmology at King's College London, discusses how the quantum mechanical Aharonov-Bohm effect may say otherwise. Though potentials are known to not be physical from a classical point of view, it is possible to demonstrate via the application of quantum mechanics that they may still hold direct influence over reality beyond being mere formulae.

What Are Fields and Potentials?

Electromagnetism is the study of how the electric and magnetic fields interact with charged objects, having been formally described under the umbrella of classical physics since 1820 at the latest. Under this theory, the electric and magnetic fields are unseen intangible zones in space emitted by charged objects in which other charged objects experience a force. The electromagnetic interactions between these fields and charges are fully described for all cases by mathematics, but the equations involved are often cumbersome and impractically complicated to solve, oftentimes asking for integration of vectors and the finding of the values for six or more variables at a time.

A voltmeter is a device used for measuring the electric potential difference between two points in an elect.

When working on some electromagnetic problems, scientists can choose to primarily work in potentials rather than directly use the field equations. Potentials are exclusively mathematical objects which arise as a result of performing certain operations on the vectors which describe electromagnetic fields, and can be thought of as the rate of flow of charge from regions of higher potential to regions of lower potential. The use of potentials conveys advantages such as removing vectors from equations, leaving only scalars which are easier to calculate, or reducing the amount of unknowns that must be found.

Potentials are regarded as a mathematical construct due to their definition; in order to use potentials in an equation, one must first define some arbitrary point in the system to act as the point of zero potential, against which the potential of all other points is measured. The aspect of potentials that has physical bearing is the 'potential difference', the difference in potential between two points. As potential difference is a difference between two quantities, the chosen reference for the values of potential ultimately does not matter. Additionally, the potential difference itself is merely a convenient way of using numbers to describe the work done by the corresponding field to move a given charge between two points.

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This non-physicality is best exemplified by the property of potentials known as 'gauge freedom', which states that one can add certain terms to the definition of the potential while still having it remain valid for the corresponding field; this implies that there are potentially infinite ways of defining a potential for the same field.

How the Quantum Realm Changes Things

At the quantum scale, however, this notion that the electromagnetic fields are physical but not the electromagnetic potentials is challenged by a phenomenon known as the Aharonov-Bohm effect; in this effect, a charged object experiences an effect due to electromagnetism, despite being in a region where the net electric and magnetic fields all cancel to zero, where this should not be possible. This effect is made possible because the object interacts with a non-zero electromagnetic potential within this zero-field region [1]. Under the classical description of electromagnetism, a zero-field region would by necessity have no potential difference, but in the quantum description, this effect at first appears to suggest that, in spite of gauge freedom implying otherwise, the potentials themselves might be physical objects, independent from the corresponding fields. However, interpretation of this surprising result has historically been debated.

What Does it All Mean?

One interpretation suggests that by giving full quantum mechanical treatment to the charges that emit the fields in question, it is possible albeit very tedious to entirely describe the Aharonov-Bohm effect treating only the charges and fields as physical objects, thus showing that the potentials remain as non-physical as they are in the classical description. [2]

Another interpretation suggests that, after developing a full quantum mechanical solution to a system exhibiting this effect, the explanation for the effect arises from the interaction of the electromagnetic potentials of both the charges emitting the net-zero fields and the charge undergoing the Aharonov-Bohm effect. [3]

Finally, yet another interpretation states that the electromagnetic fields do not offer full descriptions of electromagnetic systems, and that one must use a relativistic concept known as the electromagnetic four-potential, a unified description of the electric and magnetic potentials which also exhibits gauge freedom. From the four-potential, one can calculate the field, but due to gauge freedom the reverse is not true. This interpretation puts forward the strange prospect that not only are potentials very much physical, but that in an ironic twist they may be more fundamental than the fields from which the theory of electromagnetism was born. [4]

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But Which One's Right?

Ultimately, we don't quite know what's going on with the Aharonov-Bohm effect. What is certain is that, no matter what truly explains this phenomenon, this discovery has paved the way for an interesting reevaluation of the ultimate meaning of the mathematics that scientists use to describe reality and its relation to what we observe around us every day. If something that we thought was just a tool of convenience to simplify equations ends up being more fundamental than the equations it tries to simplify, who knows what other mysteries are hiding in the numbers?

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“On Gauge Theory”

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Research Mentor, Collaborator: Arya Lal Gonullu

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Abstract

In this research paper, the fundamental relationship between symmetry and force is established, focusing on how local gauge theories contribute to the emergence of forces. Explicit symmetry breaking, caused by external influences, and spontaneous symmetry breaking, where intrinsic properties cause asymmetry in the system's ground state, are discussed in detail to explain how symmetry breaking is essential for understanding mass and force carriers. The paper traces the evolution from classical to non-abelian gauge theories, understanding their role in the Standard model. The mathematical framework, including Lagrangian Mechanics and gauge potentials, is included to explain how these concepts formulate gauge theories. Finally, this paper summarises the application of gauge theories in particle physics, condensed matter physics, and holography. [8], [9]

Introduction

There is a strong connection between symmetry and force, such that forces come into existence due to local gauge symmetries. Gauge invariance is the principle that physical laws should remain consistent under certain transformations, requiring the addition of compensatory fields. In gauge theories, these fields appear as force-carrying particles known as bosons. [9]

In the Standard Model of particle physics, the local gauge symmetry group SU(3)×SU(2)×U(1) underlies the strong, weak, and electromagnetic forces. Each symmetry group corresponds to a fundamental force, with SU(3) symmetry describing the strong force via gluons, SU(2) symmetry describing the weak force via W and Z bosons, and U(1) symmetry describing the electromagnetic force via photons. These force-carrying particles are collectively referred to as gauge bosons. [10]

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The U(1) gauge group

The U(1) gauge group represents the simplest type of symmetry group in the Standard Model, corresponding to the electromagnetic force. Specifically, the U(1) symmetry describes invariance under local phase transformations, where each phase change can be expressed as a rotation in a complex plane by an angle θ. Mathematically, this transformation can be represented as:

$$\psi(x) \longrightarrow e^{i\theta(x)}\psi(x) \qquad [1]$$

where $\psi(x)$ is the field of a charged particle, and$\theta(x)$ is the phase, which can vary by location. [10]

In Quantum Electrodynamics (QED), the theory that describes electromagnetic interactions, this U(1) symmetry implies that the laws of physics remain invariant under local changes in the phase of a charged particle's wave function. This requirement introduces the electromagnetic field (mediated by the photon) as a compensating gauge field to preserve invariance. Thus, the photon emerges as the force carrier of the electromagnetic force. The U(1) gauge group in the Standard Model is denoted as U(1)Y, where Y represents the weak hypercharge, a quantum number related to the electric charge. [8]

The SU(2) gauge group

The SU(2) gauge group is associated with the weak nuclear force, which is responsible for processes such as radioactive decay. The SU(2) symmetry group is non-abelian, meaning that its elements (or transformations) do not commute with each other—order matters in their operations. This non-commutative nature leads to self-interactions among the gauge fields, which is crucial for accurately modelling the weak force. In the context of

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the Standard Model, the SU(2) gauge group describes the weak isospin interactions among particles, particularly affecting the left-handed components of quarks and leptons. The weak force mediators, known as the W^{+}, W^{-}, and Z^{0} bosons arise from the gauge fields of the SU(2) symmetry. Unlike the photon in QED, which is massless, the W and Z bosons are massive. This is due to the Higgs mechanism, which breaks the SU(2)×U(1) symmetry spontaneously. The mass of these bosons is responsible for the short-range nature of the weak force. [9], [10] The SU(3) gauge group

The SU(3) gauge group, which is non-abelian, corresponds to the strong nuclear force, which binds quarks together to form protons, neutrons, and other hadrons. This group, specifically denoted as SU(3)C where C stands for colour charge, underlies the theory of Quantum Chromodynamics (QCD). In SU(3) symmetry, particles called quarks come in three “colours” (analogous to red, green, and blue), and this colour charge is conserved in all strong interactions. The force carriers in SU(3) are the gluons, which, unlike photons or W and Z bosons, carry colour charges themselves. This unique property enables gluons to interact with each other, leading to a complex interaction structure that confines quarks within composite particles. The SU(3) gauge group’s self-interacting nature is crucial for the strong force’s characteristics, such as colour confinement, where quarks cannot exist in isolation but are always bound together. [8], [9]

Early Ideas and Classical Gauge Theory

The concept of gauge invariance was first proposed by Hermann Weyl in the 1920s as part of his attempt to unify gravity and electromagnetism. Weyl suggested that scale invariance (the invariance of physical laws under scaling of lengths) could provide the basis for a unified theory of these forces. However, his model implied that atomic sizes could change based on location and time, contradicting observable phenomena. Despite this flaw, Weyl’s work laid critical groundwork for the later development of gauge

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theories. Following on from this, Noether’s theorem formalises the connection between symmetry and conservation laws, stating that each continuous symmetry of a physical system corresponds to a conserved quantity. For instance, time-translation symmetry leads to the conservation of energy, and, spatial translation symmetry corresponds to momentum conservation.[7], [9] Electromagnetism

The first successful Abelian gauge theory was Quantum Electrodynamics (QED), a theory that describes the interaction between light (photons) and matter (charged particles). QED is a relativistic quantum field theory built upon the U(1) gauge group, a group that mathematically expresses the symmetry associated with electromagnetic interactions.

Non-Abelian Gauge Theories and the Standard Model

In 1954, Chen Ning Yang and Robert Mills generalised the concept of gauge invariance to non-abelian groups, leading to the development of Yang-Mills theories. Unlike abelian gauge theories like QED, non-abelian gauge theories involve gauge fields that can interact with each other. [8], [10](Weinberg, 1995)

Symmetry

Symmetry in physics refers to invariance under certain transformations. For example, a sphere is symmetric under rotations because it looks the same from any angle. In physical systems, symmetries often correspond to conservation laws, as articulated by Noether's theorem. However, not all symmetries are apparent in the observed state of a system. Symmetry breaking occurs when the laws governing a system are symmetric, but the state of the system is not. The symmetry breaking process can occur either explicitly or spontaneously. [1], [9] Consider a thin, long cylinder balanced on one end. The cylinder, while balanced, has rotational symmetry—it looks the same from any angle around its

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axis. However, this symmetry is fragile. As soon as the cylinder tips over, it falls in one specific direction, breaking the symmetry. The laws governing the cylinder (such as gravity and the shape of the pencil) have not changed, but the final state of the system (the cylinder lying in one direction) no longer has rotational symmetry. This is an example of spontaneous symmetry breaking, where a system governed by symmetric laws settles into an asymmetric state.

Explicit Symmetry Breaking occurs when the symmetry of a system is broken due to external influences or terms added to the equations of motion. For example, adding a magnetic field to a symmetric spin system explicitly breaks its rotational symmetry. [8]

The other type of symmetry breaking is Spontaneous Symmetry Breaking (SSB), where the underlying laws, such as those expressed through the Lagrangian and Hamiltonian (which describe the system energy and dynamics), are symmetric, but the ground state (the state of lowest energy) of the system is not. [1]

Mathematical Framework

Lagrangian Formulation

In gauge theory, the Lagrangian density describes the dynamics of fields, which remains invariant under local gauge transformations. This invariance is essential, as it ensures that physical laws are consistent across different reference frames. The Lagrangian density in a gauge theory includes terms that represent the gauge fields themselves and their interactions with matter fields. For example, in Quantum Electrodynamics (QED), the Lagrangian incorporates the electromagnetic field tensor and describes its interaction with charged particles.

For spontaneous symmetry breaking in U(1) gauge theory, derived from the electrodynamics of spin-0 charged particles, a new complex scalar field is introduced, described by the Lagrangian density:

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$$\mathcal{L} = D_{\mu}\phi^{*}D^{\mu}\phi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \nu(\phi) \quad [2]$$

where $D_{\mu}\phi = \partial_{\mu}\phi + ieA_{\mu}\phi$, $F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$ and ν being the sombrero potential of the Goldstone model. This field acquires a non-zero average value that allows the symmetry to be broken spontaneously. [9]

The Higgs Mechanism

In the context of gauge theories, SSB is crucial for understanding how particles acquire mass. Consider a system with a symmetric potential. At high energies (or temperatures), the system maintains its symmetry. However, as the system cools or the energy decreases, it may settle into a state that breaks this symmetry.

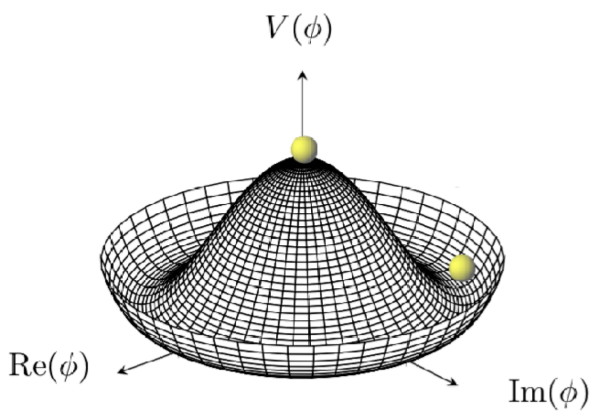

Figure 1. shows At each point in the field, a particle has a certain mass. At the top of the field, at high energies, the mass is zero and there is symmetry. Around the bottom of the hill are different, non-zero masses, at the lowest possible energy state, but it is asymmetric.

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To illustrate this the “Mexican Hat” or “Sombrero” potential is commonly used, which has a symmetric shape resembling a sombrero. The potential is symmetric around a central point, but the lowest energy states form a circle around this centre. A system in this potential will settle at a point on the circle, breaking the symmetry because the specific location on the circle is arbitrary but chosen by the system. [4]

The Lagrangian for the Higgs field Φ can be expressed as:

$$\mathcal{L} = |D_{\mu}\phi|^2 - V(\phi) \qquad [3]$$

where D_{μ} is the gauge-covariant derivative, $V(\phi)$and the potential is given by:

$$V(\phi) = \mu^2|\Phi|^2 + \lambda|\Phi|^4 \qquad [4]$$

For$\mu^2 < 0$, the potential takes the Mexican hat shape. The field acquires a vacuum expectation value $\langle\Phi\rangle$, breaking the symmetry.

The concept of the “sombrero” potential can be illustrated mathematically through a potential function, the Goldstone model:

$$\nu = \frac{1}{2}\lambda(\phi^2 - \frac{1}{2}\eta^2)^2 \qquad [5]$$

where λ and η are positive constants and ϕ is a complex scalar field of the type $\phi(t, r)$. As already stated, this potential has a maximum at ϕ=0 and a minimum around a circle, the ground state, which in this case is defined by the vacuum state $|0\rangle$. This vacuum state is said to be degenerate and can be described by the following function:

$$\langle 0|\phi|0\rangle = \frac{\eta}{\sqrt{2}}e^{i\alpha} \qquad [6]$$

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where α is an independent variable. From this relation, with α=0, we can derive the vacuum expectation value of ϕ as follows:

$$\phi = \frac{1}{\sqrt{2}} (\eta + \phi_1 + i\phi_2) \qquad [7]$$

substituting this value back into the potential function ν we have:

$$\nu = \frac{1}{2}\eta^2(\phi_1^2 + \phi_2^2) + \frac{1}{4}\lambda(\phi_1^2 + \phi_2^2)^2 \qquad [8]$$

The curvature of the potential in the direction of the mass of the ϕ_1 boson, which represents radial oscillations. These oscillations generate massless modes defined as "Nambu-Goldstone bosons", space-dependent oscillations in the direction of symmetry breaking. These bosons, however, didn't solve the problem posed in the spontaneous breaking of a continuous symmetry: the appearance of massless scalar bosons (intermediate boson states with zero energy in the limit of zero momentum). This is shown in the proof for the Goldstone theorem (on which also Salam, Weinberg, et al. worked on):

$$\delta\varphi(t, r) = i\epsilon[\varphi(t, r), Q(t)] \qquad [9]$$

with ϵ being an infinitesimal parameter, this commutator gives the change in any field φ under any infinitesimal symmetry transformation.

The Goldstone theory is said to be Lorentz invariant, as the "charge" operator Q of the commutator $\delta\phi$(t,r) is time-independent: this means that transformations can occur only with the possibility of massless particle states.

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Mass Terms

Once the symmetry is broken, the originally massless gauge fields gain mass. This is seen in the gauge-covariant derivative term, where the interactions between the Higgs field and the gauge fields generate mass terms:

$$m_W = \frac{1}{2} g v, \quad m_Z = \frac{1}{2}\sqrt{g^2 + g'^2}\, v \qquad [10]$$

Here, v is the vacuum expectation value of the Higgs field, g andg' are the coupling constants for the $SU(2)$ and $U(1)$ groups, respectively. The mechanism predicts a new particle, the Higgs boson, which was experimentally confirmed in 2012 at CERN.

To further understand the vacuum expectation value, a new field $B_\mu$can be defined, as was previously done for the derivation of the vacuum expectation value with α=0 in equation [4]:

$$B_\mu = A_\mu + \frac{1}{e\eta}\partial_\mu \phi_2 \qquad [11]$$

where the relation between A_μ and B_μ is a gauge transformation, allowing the radial ϕ_1 mode to acquire mass from the curvature of the potential (i.e. the Higgs boson) and the kinetic term for ϕ_2 to turn into a mass term for B_μ, therefore, we can define the Lagrangian:

$$\mathcal{L} = \frac{1}{2}\partial_\mu \phi_1 \partial^\mu \phi_1 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\lambda\eta^2\phi_1^2 + \frac{1}{2}e^2\eta^2 B_\mu B^\mu + \textit{cubic and quartic terms}$$

[12]

where no massless field appears, but a massive gauge boson and a massive scalar, i.e. the Higgs boson. This Lagrangian will be the basis for the formulation of the Standard Model, in which the Higgs boson plays a fundamental role, namely in the understanding of the mechanism that gives masses to gauge bosons while escaping the Goldstone theorem.

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Discussion

Electroweak Theory

The electroweak theory is based on the $SU(2) \times U(1)$ gauge group. The $SU(2)$ part describes the weak isospin interactions, while the $U(1)$ part is related to the weak hypercharge. Through the Higgs mechanism, this symmetry is spontaneously broken, resulting in the distinct electromagnetic and weak forces we observe at low energies. Specifically, with this theory, they managed to show that, by a mixing mechanism between neutral gauge bosons, one (the photon) would have parity-conserving interactions and the others (such as W^+ and W^-) would not, an acknowledgement that previous models failed to achieve. The electroweak unification predicts the existence of massive gauge bosons: the W^+, W^-, and Z_0 bosons, which mediate the weak force, and the massless photon, which mediates the electromagnetic force. Furthermore, the combined gauge group $SU(2) \times U(1)$ is a crucial part of the Standard Model, describing how particles acquire mass through the Higgs mechanism, as a matter of fact, the masses of the W and Z bosons are a result of this mechanism.[8], [9]Non-Abelian Gauge Theories and the Standard Model

Specifically, the Yang-Mills theories are based on the application of the gauge invariance principle on the isospin $SU(2)$ group (a hadronic symmetry group relating the u and d quarks): inserting symmetry-breaking terms in isospin symmetry groups generated inconsistencies with basic properties of gauge theories, mainly for isospin not being an exact symmetry. Therefore, it ended up being an incorrect theory of strong interactions, which will nevertheless find a successful outcome with the Quantum Chromodynamics gauge theory (QCD), based on the $SU(3)$gauge group. It describes how quarks and gluons interact. Gluons are the force carriers of the strong force, and their self-interactions are a direct consequence of the non-abelian nature of the $SU(3)$group. As mentioned earlier, the electroweak theory unifies the electromagnetic and weak forces. [2]

In all the models presented above, the symmetry breaking, due to the large masses of W^+ and W^-, had to be inserted by hand. Hence, the suggestion by Nambu that the mass-gaining process could be achieved through spontaneous symmetry breaking (SSB).

Spontaneous Symmetry Breaking and the Higgs Mechanism

Further models were developed than those mentioned in the introduction, namely, the ones presented in 1964 that would have led to the formulation of the present Standard Model, the theory describing three of the four known fundamental forces in the universe (electromagnetic, weak, and strong interactions) and classifying all known elementary particles: those models were proposed by Englert and Brout, by Higgs and by Guralnik.

The Higgs theory posits a scalar field known as the Higgs field, which permeates all of space. The potential energy associated with the Higgs field has the shape of a Mexican hat.

The Lagrangian describing the electroweak interaction is symmetric under the SU(2)×U(1) gauge group. This symmetry implies that the gauge bosons, W and Z bosons, and the photon, should be massless.

As the universe cools down after the Big Bang, the Higgs field acquires a non-zero vacuum expectation value. The field settles in a specific point in the Mexican hat potential, breaking the symmetry spontaneously.

The broken symmetry allows some gauge bosons to acquire mass through their interactions with the Higgs field. Specifically, the W and Z bosons gain mass, while the photon remains massless, corresponding to the electromagnetic force.

The introduction of the Higgs mechanism raises essential questions. For instance, the requirement that the Higgs field have a non-zero vacuum expectation value might seem arbitrary. One might argue that this assumption lacks a deeper theoretical justification, especially since the negative μ^2 term is introduced primarily to enable spontaneous symmetry breaking. However, proponents counter that the Higgs mechanism explains

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how gauge bosons acquire mass without violating gauge invariance. This symmetry breaking framework is arguably more natural than adding the mass terms "by hand", as was attempted in earlier particle physics models. [4], [5]

Another criticism concerns the Higgs potential itself, especially whether the "Mexican hat" or "sombrero" shape is the only viable option. Some theorists have proposed alternative mechanisms for symmetry breaking that do not rely on this specific form. One possibility is that a more complex or higher-order potential could lead to similar results, potentially exploring phenomena like neutrino mass or dark matter within a modified symmetry-breaking framework. Despite these suggestions, the effectiveness in yielding accurate predictions for particle masses has made it the prevailing model.

Moreover, the appearance of Nambu-Goldstone bosons is another point of theoretical debate. In spontaneous symmetry breaking, Goldstone's theorem predicts the emergence of a massless scalar boson associated with broken symmetries. In the Higgs mechanism, the gauge fields associated with broken symmetries become massive, thus avoiding the issue of massless Goldstone bosons. However, some theorists question if alternative symmetry-breaking methods could avoid introducing such scalars altogether, which could simplify the model. Nevertheless, the Higgs field's ability to generate masses for gauge bosons in a manner consistent with electroweak symmetry breaking remains a compelling advantage of the model.

Finally, some claim that the Higgs mechanism lacks empirical rigour due to its reliance on the vacuum expectation value. This vacuum based origin of mass is difficult to observe directly, and until the 2012 discovery of the Higgs boson at CERN, it was largely theoretical. Yet, the successful detection of the Higgs boson confirmed many predictions of the standard model, giving significant credibility to the Higgs mechanism. While the Higgs boson's properties align well with theoretical predictions, ongoing research is examining if alternative scalar fields or multiple Higgs-like particles could explain phenomena that the standard model could not fully address, such as the hierarchy

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problem or the nature of dark matter: one valuable example is given by the theoretical "X17 boson", registered as an anomalous 16.8 MeV emission (hence the name X17) inhibited by the emission of electron-positron pairs in the $^{7}Li(p,e^{+}e^{-})^{8}Be$ and $^{3}H(p, e^{+}e^{-})^{4}$ nuclei reactions performed in the ATOMKI experimental setup. [1], [9]

Thus, while the Higgs mechanism is widely accepted, alternative models and modifications are being explored to address its limitations.

Conclusion

Symmetry and gauge invariance are central concepts in physics, with the Standard Model describing fundamental forces through gauge symmetries. Symmetry breaking through the Higgs mechanism, allows particles to acquire mass and plays an important role in the structure of particle interactions. While gauge theories have provided understanding, especially in the standard model, they also call attention to the areas where our understanding remains incomplete.

Applications in Particle Physics

The Standard Model is a gauge theory based on the symmetry group SU(3)×SU(2)×U(1)). It successfully describes the electromagnetic, weak, and strong interactions, providing a framework for understanding the behaviour of elementary particles. The model has been extensively tested and confirmed through experiments, making it one of the most successful theories in physics.

Despite its success, the Standard Model is incomplete, as it does not incorporate gravity and fails to explain certain phenomena, such as dark matter and neutrino masses. Theories beyond the Standard Model, such as supersymmetry and string theory, attempt to address these limitations by extending the principles of gauge theory. [9], [10]

General Relativity and Gauge Theory

While general relativity is not a gauge theory, it shares similarities with gauge theories, particularly in its treatment of spacetime as a dynamic entity. Efforts to quantize gravity often employ gauge-theoretic concepts, seeking a unified framework for all fundamental forces. [8]

Condensed Matter Physics

Gauge theories have applications beyond particle physics, particularly in condensed matter physics. They provide a framework for understanding phenomena such as superconductivity and the quantum Hall effect, where gauge symmetries play a crucial role in describing the behaviour of many-body systems.

Holographic duality

Gauge theory is related to gravitational theories in higher dimensional space. Gravity in a higher-dimensional space (d+1 dimensions) emerges holographically from a gauge theory in one lower dimension (d dimensions). A feature of this is its strong-weak duality where gauge theory is strongly coupled but gravity interacts weakly. The physical applications of this relationship involve investigating the behaviour of quark-gluon plasma and gravity/fluid correspondence.

The relationship between gauge theory and gravitational theories comes from the conjectured relationship between anti-de Sitter spaces and conformal field theories. However, there are still questions about how the geometry and local excitations on the gravity side are encoded in the dual non-gravitational theory. [3] Gauge theories, therefore, have had an impact on both experimental and theoretical physics. As researchers explore beyond the Standard Model, these concepts will remain decisive in formulating and testing new hypotheses. The ongoing study of gauge theories advances our knowledge of particle physics and offers insights into the broader structure of the cosmos.

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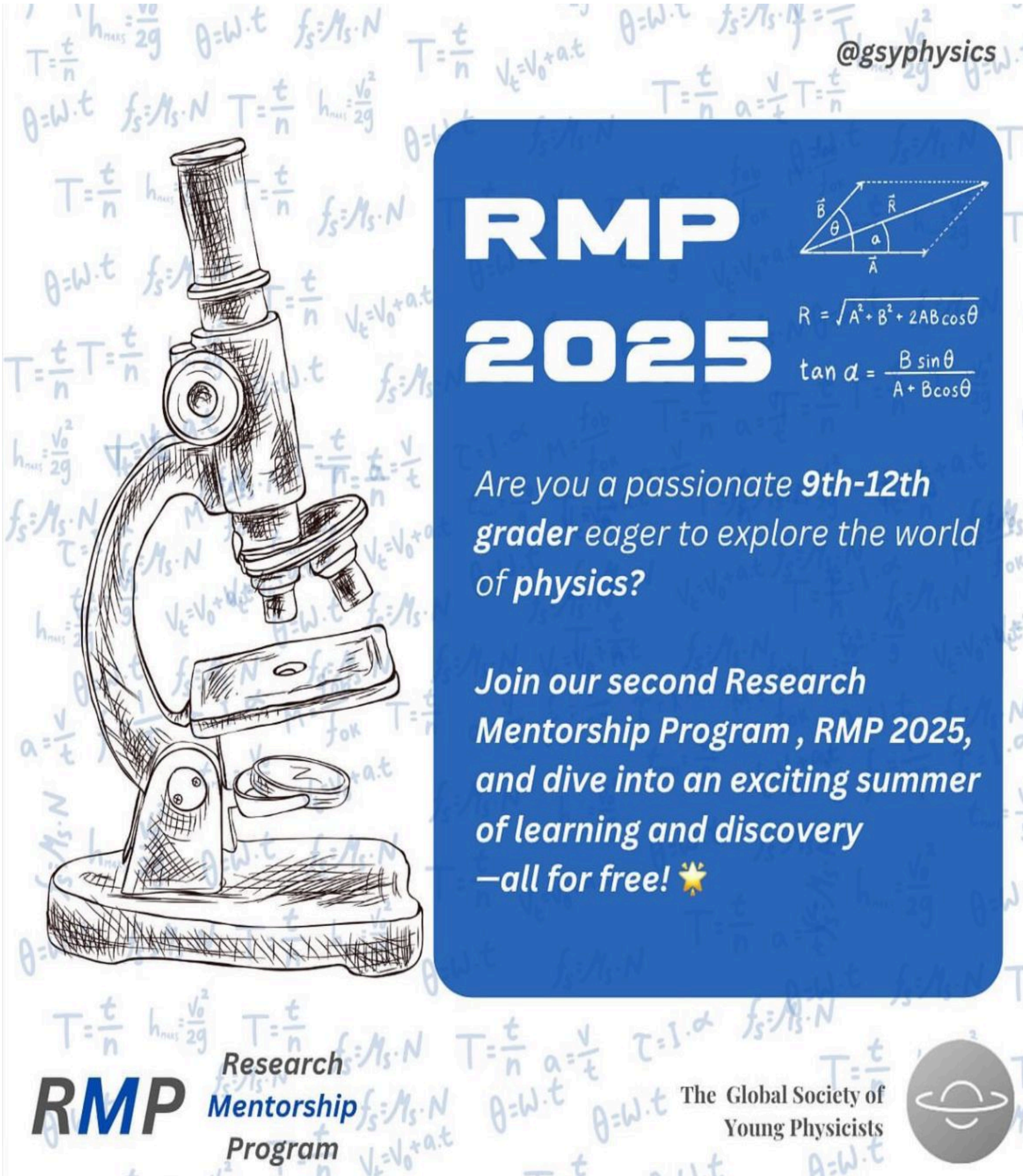

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CONTRIBUTIONS

Arya Lal Gonullu, Chief Executive of GSYP and Editor of the August issue of *The Starry Messenger*, named the science magazine after Galileo Galilei's groundbreaking work, *Sidereus Nuncius* (The Starry Messenger). In this historic book, Galileo had unveiled three revolutionary discoveries he made with it: Sunspots, the Moons of Jupiter and that the Moon is not a perfect sphere. Gonullu hopes that physics will soon experience a new "Starry Messenger" breakthrough through the new rising stars of the field.

Editor of *The Starry Messenger*: Sherlyn Nammi

Deputy Editor of *The Starry Messenger*: Leah Levy, Piyamini Tenahandi

Poster Design : Chiara Alegri, the Head of Marketing at GSYP

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