The Quest for Quantum Gravity and the Applications of AI

Achyut S. Chebiyam

Abstract

Quantum mechanics and classical physics, two of the most important branches of science explaining our world, are contradicting in nature. The search for a Grand Unified Theory of the universe that would be able to link these two branches so far with concrete foundations has been to no avail. So far, gravity has successfully been able to describe the movement of planets and stars. Quantum physics describes the physics of the subatomic world. Unfortunately, gravity currently has no concrete basis in quantum theory, the most prevalent theories describing human understanding of the universe are incompatible. Using various research papers and articles, this paper reviews the different theories addressing the gap in our understanding such as String Theory and Loop Quantum Gravity and why they may fit with our expectations as well what shortcomings they have. Discovering a bridge between quantum physics and gravity may give us new insight that we can incorporate into technology. Furthermore, we would have a more complete general understanding of the mechanics of our universe. This review paper is aimed at helping physics aspirants understand the development of the theory of gravity and the various candidates for the Grand Unified Theory. It also highlights the applications of artificial intelligence in advancing our understanding of the cosmos at its most fundamental level.

Introduction

Gravity is a fundamental aspect of the world that humans have explored scientifically and mathematically. However, a complete description of gravity still eludes the scientific community. This paper highlights the major advances in gravitational research that has led to our current understanding of the world and how quantum gravity is needed for us to gain a clear picture of our universe. It also highlights some of the leading candidates for the Grand Unified Theory and how artificial intelligence (AI) is accelerating research. I include an introduction to different theories of gravity and quantum mechanics and how human understanding of such phenomena has evolved over time. This paper is deliberately crafted to cater to readers of all backgrounds, ensuring accessibility to readers of limited mathematical maturity and enabling younger audiences to comprehend the fascinating growth of quantum gravity. For those readers with an interest in delving into the mathematical intricacies, the appendices referenced within the text offer a valuable resource.

As humans, we are driven to understand the enigmas around us, and the nature of gravity is no exception. Formulating a Grand Universal Theory would signify a historic landmark in our understanding of nature, paving the way for scientific exploration. This knowledge may enable us to explore phenomena such as black holes, cosmic inflation, and dark energy and matter through a new lens.

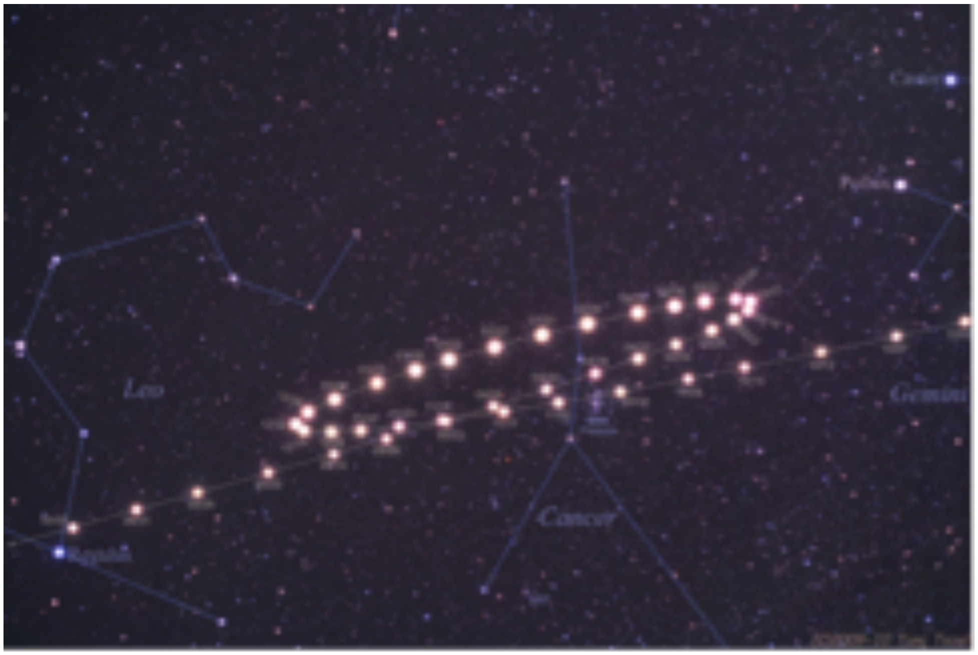
Moreover, unraveling the mysteries of quantum gravity could have profound practical implications. This knowledge might lead to the development of revolutionary materials, novel energy solutions, and advancements in medicine, enhancing multiple facets of human life.

The exploration of quantum gravity matters because it has the potential to reshape our understanding of the universe, revolutionize technology, and uncover the secrets of the cosmos. As we venture into the depths of this captivating field, we discover more about the complex and meticulously-planned layout of our surroundings. In many ways, advancement in this field is a voyage into the wonders of our universe.

Heliocentrism and Newton's Gravitation

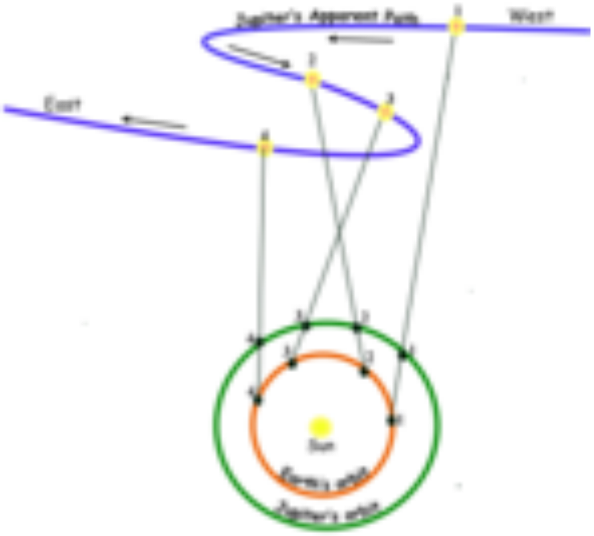
From the dawn of civilization, humans have contemplated their place in the universe from philosophical and scientific standpoints. To understand our place in the universe, early scientists focused on the cosmos; one can only understand humans' position in the universe by observing our planet's surroundings.

Most celestial bodies conformed to the trend of repeated cycles tracing the sky, what we now recognize as constellations. But, as first century Roman astronomer Claudius Ptolemy realized, certain bodies did not follow this pattern [1]. The observable planets Mercury, Venus, Mars, Jupiter, and Saturn followed retrograde motion [2]. This meant that the movement of a particular celestial body was not in accordance with the movements of the rest of the universe.



Planetary motion of Mars from Earth's perspective in June, 2010 [3]

The picture above displays a digitally stacked image of the planetary motion of Mars from Earth's perspective in June, 2010 [3]. Constellations appear to revolve around the Earth, yet Mars created a loop in the sky by appearing to move backward for some time. Ptolemy recorded this information for the observable planets [2]. But why does this abnormal planetary motion occur?



Jupiter's Retrograde Motion from Earth [4]

As shown by the diagram above, viewing the motion of two revolving planets from one of them leads to only a partial perspective gained. It appears as though the planet, in this case Jupiter, traces out an abnormal curve in space, although from a larger perspective, it is apparent that Jupiter's path appears distinct from stars because of its orbit around the Sun.

At the time, however, a heliocentric model of the universe (planets revolving around the Sun) was unheard of. Rather, scientists believed that Earth was the center of the universe, which led Ptolemy to compile his observations in a geocentric (Earth-centered) model, as shown below [5]. In this model, every celestial body revolves around the Earth, and some follow smaller orbits within their large arcs around the Earth.

Ptolemaic model of the universe [5]

It wasn't until the 16th century when Polish astronomer Nicolaus Copernicus proposed a heliocentric model of the universe according to his naked-eye observations of the firmament [5]. His notions were so radical that they took over a century to become accepted in the scientific community [5].

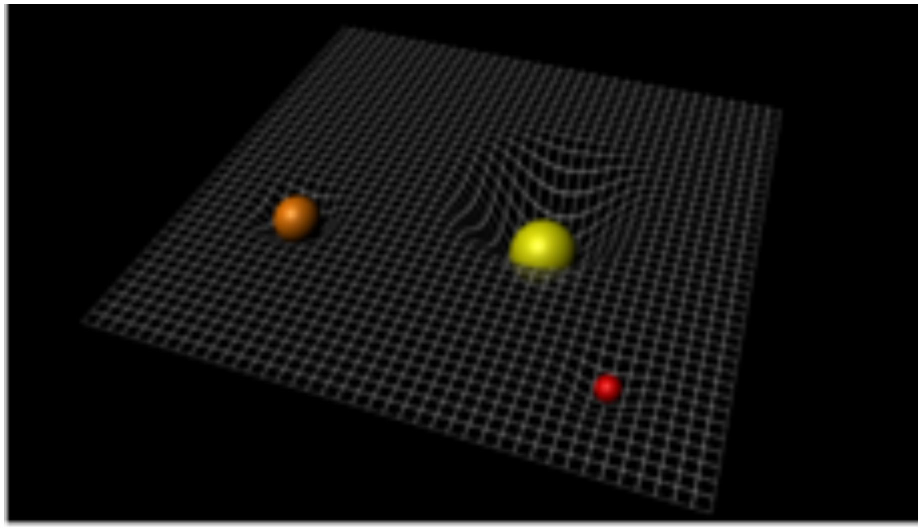
Copernicus correctly interpreted astronomical data as proof of a heliocentric model, but it was German mathematician Johannes Kepler who derived mathematical equations to precisely predict planetary motions [6]. He created what we still use today as Kepler's Laws of Planetary Motion, describing the elliptical routes of orbiting planets.
Sir Isaac Newton understood that Kepler's Laws correctly define planetary motion, so he extended the idea to create three universal laws that describe all types of motion: Newton's Laws of Motion [6]. He realized that all motion follows the same universal rules and that they can be explained by the same basic principles, whether the object is any of the massive stars or an apocryphal apple falling from a tree. He presented his findings in the 1687 book *Philosophiae Naturalis Principia Mathematica*, meaning "Mathematical Principles of Natural Philosophy," igniting the scientific revolution notion that philosophy can be defined by science [7]. Within the pages of his book, Newton recognized a fundamental force of attraction exerted by all objects: gravity.

Newton's Laws succeeded in creating a theoretical framework for our solar system, but failed to answer many pressing questions. What causes the force of attraction? Why do all objects have it? Why is Mercury's orbit so unnatural? All of these questions remained a mystery until Albert Einstein's 1915 publication of the Theory of General Relativity [8].

General Relativity

Rather than a force, Einstein defined gravity as a curvature in space-time resulting from the presence of mass and energy [9]. The presence of matter of energy distorts spacetime itself, as shown in the figure below.

This theory implies that the landscape of the universe is constantly evolving with the motion of celestial bodies and that gravity is actually a distortion of spacetime rather than a force [10]. But what does that mean? Imagine you are sipping a cup of tea in a space station. Newton's theory of gravity as a force argues that celestial bodies exert a large enough force that you, the cup of tea, and the space station are pulled toward them. On the other hand, Einstein's depiction of a distortion in spacetime elucidates that the event of you sipping tea in the space station itself is distorted by the presence of matter and energy. A curvature of spacetime itself causes the apparent gravitational attraction.

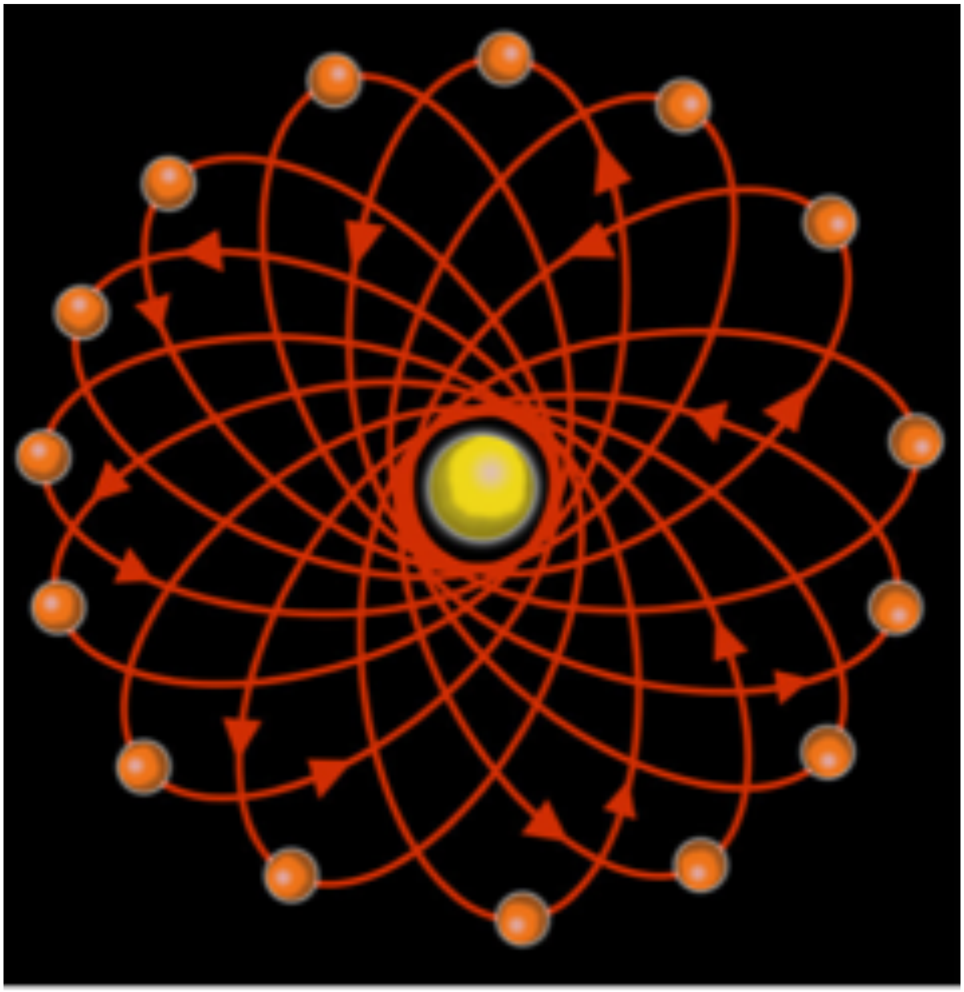


Matter's distortion of spacetime [10]

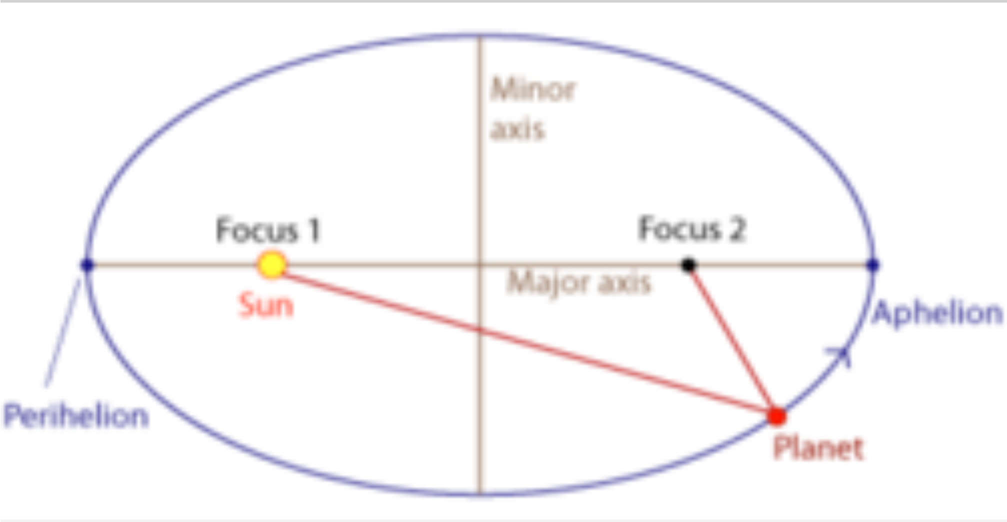
Newton's Laws failed to explain the irregular motion of Mercury's orbit [11]. Planets revolve around the Sun in elliptical formations, and these ellipses themselves revolve around the Sun. This elliptical revolving motion is known as precession. But Mercury not only jiggled in its orbit, but made its rounds faster than expected [11].

Astronomers were thrown off. They assumed that a mystery planet called Vulcan was causing these gravitational anomalies [11]. After it failed to be detected, astronomers deduced that an asteroid field or invisible cosmic dust was causing Mercury to precess ahead of schedule, yet neither of these were detected either [11].

As astronomers thought of gravity as forces between objects, they were unable to explain this. But Einstein, who had outlined gravity as mass distorting space-time, understood that Mercury's strange precession was caused by Mercury's proximity to the Sun's warping of space-time [11].



Mercury's abnormal orbit around the Sun [12]



Elliptical orbit of a planet (exaggerated) [13]

For example, imagine drawing the elliptical motion of a planet about the Sun on a sheet of paper, referencing the diagram above. Now cut along the line from the aphelion (farthest point from the Sun) to the Sun. Then overlap the two flaps of paper slightly and watch as the paper distorts into a three-dimensional cone-like structure and the orbit length is reduced. For two hundred years, astronomers were baffled by the resultant shorter route Mercury, but Einstein's theory of relativity correctly predicted its fastened orbit as a cause of a space-time distortion [11].

The final test for Einstein's Theory of General Relativity was its effect on light. According to Newton's theory, light is massless and therefore has no correlation with the effects of gravity; so it should travel straight regardless of nearby massive bodies. But according to Einstein, light should be deflected by the effects of some celestial bodies' large masses. The idea of experimentally discovering this was planned out. Pictures would be taken of a specific view of stars at two different times, one with the Sun there and one without. If the stars in a line of sight closer to the Sun were obscured, Newton's theory was right. If the starlight still reached Earth by bending around the Sun and the star appeared to be in a slightly different position, general relativity prevailed. But to take a picture of stars in the presence of the Sun, scientists figured that they had to wait for a solar eclipse so that the moon's shadow would ensure that the Sun's light wouldn't blind starlight out in photographs [14].

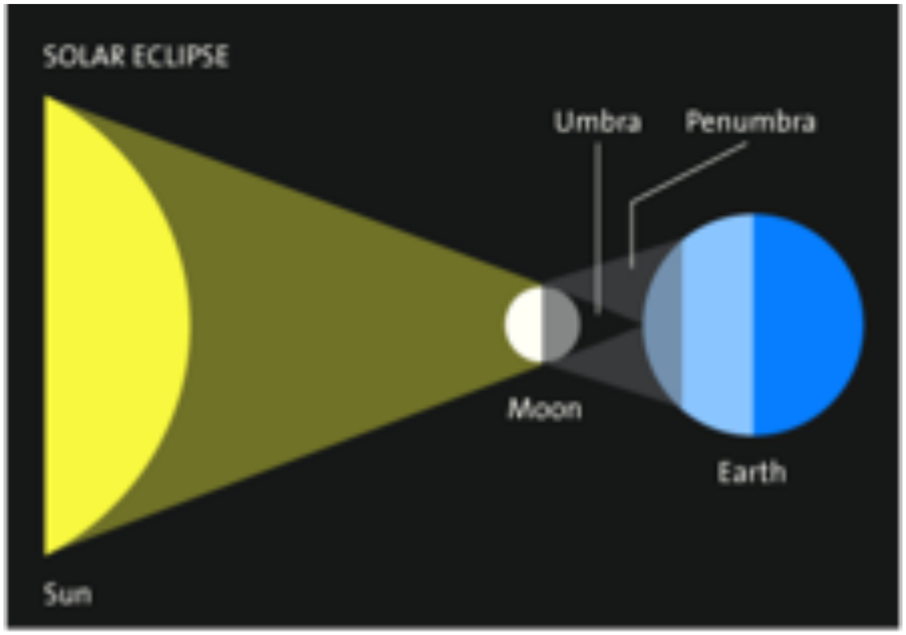
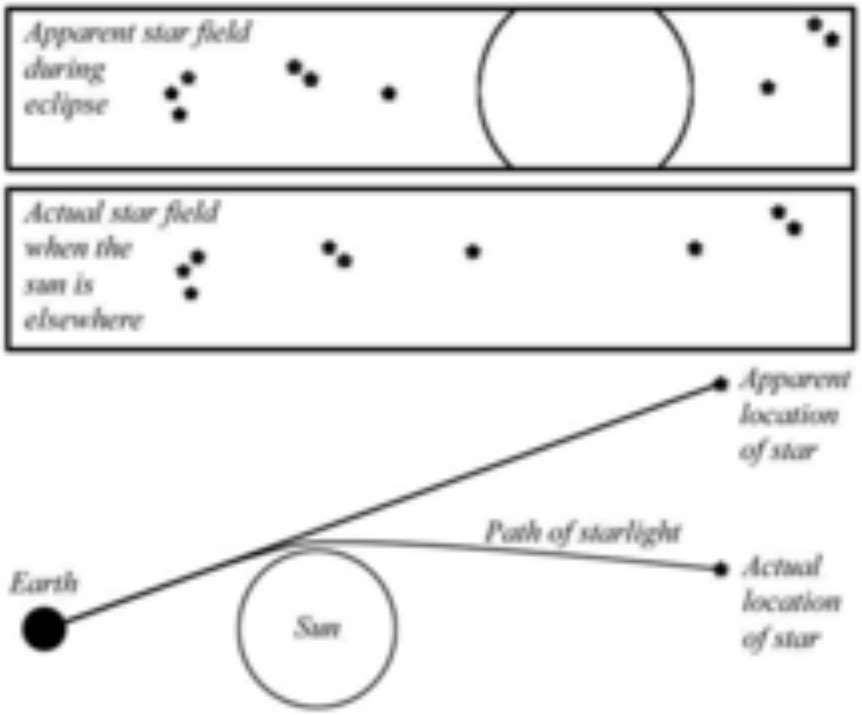


Diagram of solar eclipse [14]

After Einstein's publication of the theory of relativity in 2015, there were few solar eclipse opportunities to test for this [15]. World War 1 interfered with the 1916 eclipse and clouds defeated observation in the 1918 eclipse, but during the seven-minute 1919 solar eclipse, Arthur Eddington successfully led an expedition to photograph stellar positions in Brazil and Africa [15].

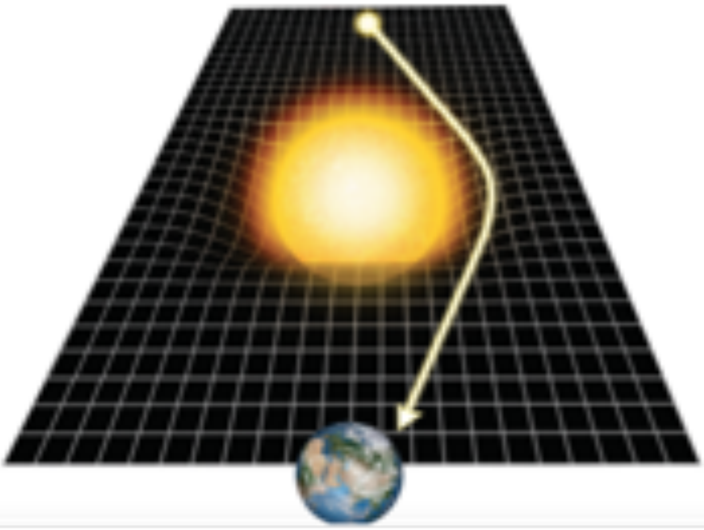


Gravitational lensing test [15]

Careful analysis of the data demonstrated how the star's position had seemingly moved in the Sun's presence, proving that Einstein was right. The framework of general relativity had defeated Newton's gravitational attraction in the search for a theory of the universe. Nowadays, we call this phenomenon gravitational lensing and see it in images of black holes as light bends around its extraordinary mass.

Black hole bending light [16]

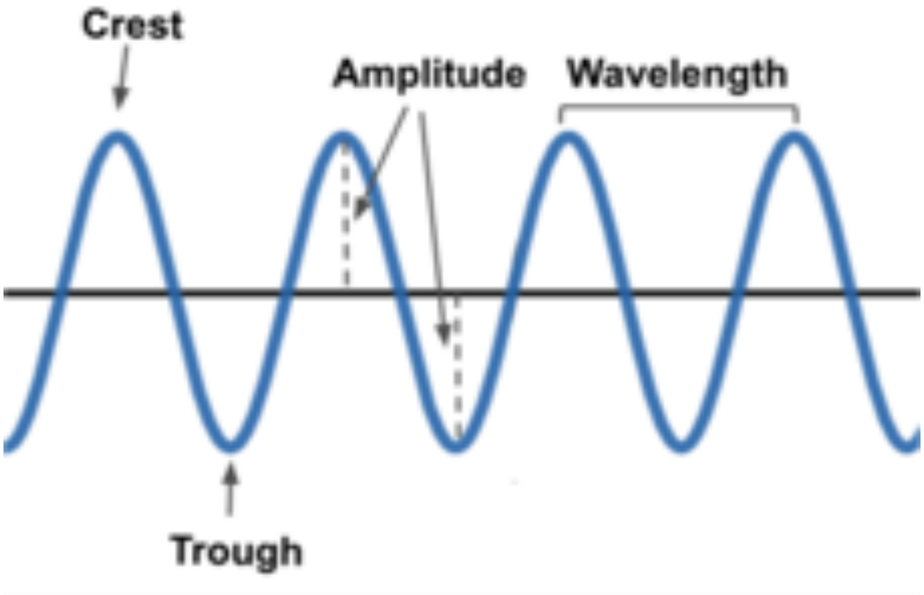
Additionally, gravitational lensing is proof of general relativity because the speed of light is constant. The bending of light implies that the light travels a longer distance to reach Earth. If speed has to remain constant and the distance traveled is increased, then the time taken has to be greater too. Such is the effect of the Sun and massive bodies: they slow time down around them.



Starlight warping around Sun to reach Earth [17]

Quantum Mechanics and the Standard Model of Particle Physics

Having delved into the domains of gravitational lensing and the profound significance of the 1919 solar eclipse, we now immerse ourselves in the wondrous realm of quantum physics. The resounding success of the 1919 eclipse not only validated Einstein's theory of general relativity but also triggered a scientific renaissance that challenged the fundamental notions of classical physics to its core.



Properties of waves [67]

Rayleigh-Jeans Law

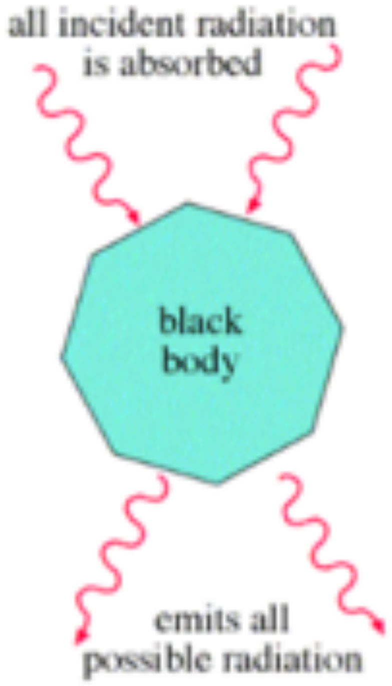
In 1900, Lord Rayleigh derived the following formula, and a derivation including the proportionality constant and empirical evidence was compiled by Rayleigh and Sir James Jeans from 1905-1909 [20]:

$$\frac{dU}{d\lambda} = \frac{8\pi kT}{\lambda^4}$$

Where $\frac{dU}{d\lambda}$ is the rate of change of energy density U with respect to wavelength λ , k is Boltzmann's constant, and T is temperature in Kelvin

[The detailed derivation of this formula can be found in Appendix A]

A blackbody is an idealized object that absorbs and emits all energy but cannot reflect any [23]. In context, Rayleigh-Jeans Law expresses the relationship between the rate of change of energy density and wavelength for blackbody radiation at temperature T.



Blackbody absorbs and emits all radiation but cannot reflect [66]

However, there is a significant problem with this formula when it is used for smaller wavelengths. If we take the limit of $\frac{dU}{d\lambda}$ as λ tends to 0, we see that:

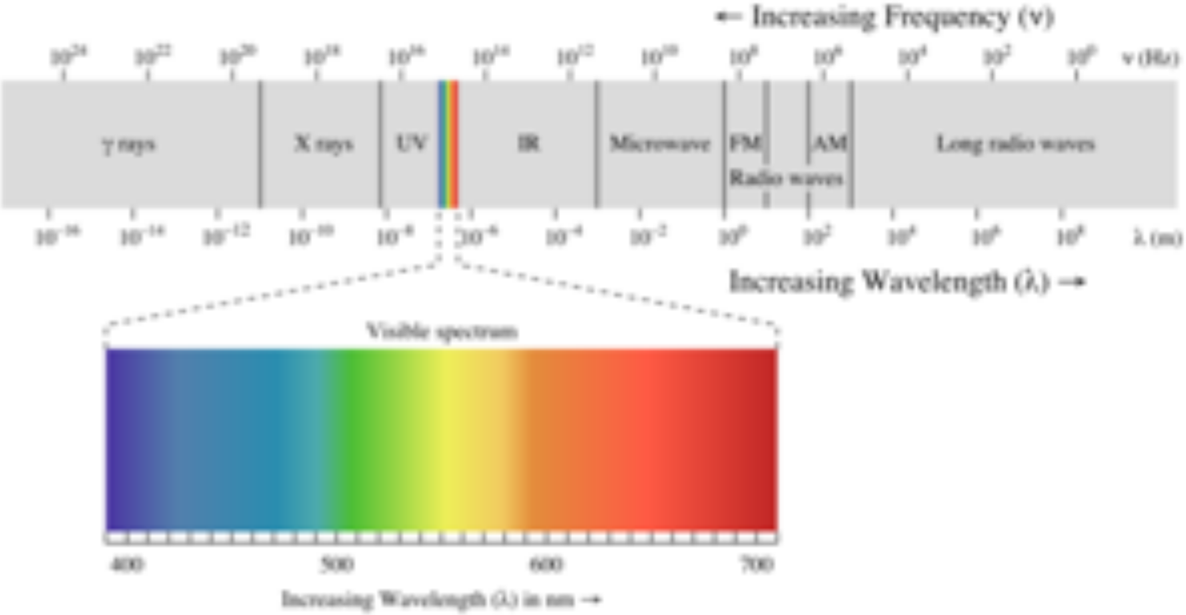
$$\lim_{\lambda \to 0} \frac{dU}{d\lambda} = \lim_{\lambda \to 0} \frac{8\pi kT}{\lambda^4} = \infty$$

As λ approaches 0, the denominator of $\frac{8\pi kT}{\lambda^4}$ becomes infinitesimally smaller as the numerator remains constant. The result of this ratio is an infinitely large energy density with respect to wavelength.

This implies that as the wavelength decreases (approaching the ultraviolet range), the energy output becomes infinite. A blackbody would emit infinite amounts of energy as the wavelength approached ultraviolet range [23]. This possibility is clearly unrealistic and is a breakdown of the Rayleigh-Jeans Law. It quickly became known as the Ultraviolet Catastrophe because a law that had been derived from a common classical physics formula no longer correctly reflected the mechanics of the universe.

Electromagnetic Theory and Planck’s Law

Fortunately, in the late 19th century, German physicist Max Planck was asked by the German Bureau of Standard about how to maximize the light output of a lightbulb while minimizing electrical power consumption [21]. Planck realized that light is made up of electromagnetic waves that, at different frequencies, exhibit different colors [21]. He sought to maximize the amount of light emitted from the filament that specifically is in the visible spectrum, so that the lightbulb would be most effective.



Visible spectrum of light in context of electromagnetic spectrum [23]

At first, Planck attempted to work with the existing framework of electromagnetic theory, but there was a consistent disconnect between the theoretical conclusions and experimental results [21][22]. Instead, Planck began to work backward by trying to formulate electromagnetic equations from experimental data [22]. Planck, out of desperation, went off script: he contemplated the radical notion of atoms not emitting continuous radiation, but rather radiation in discrete bundles called quanta [21][22].

By assuming that standing electromagnetic waves in cavities were quantized in energy, Planck was able to construct a new framework for electromagnetic emission starting with a formula from empirical evidence:

$$E = \frac{hc}{\lambda}$$

Where E is energy, h is Planck’s constant, c is the speed of light, and λ is wavelength [18].

From this relationship, Planck derived a corrected equation for electromagnetic emission. The average energy per unit mode per unit volume is given by:

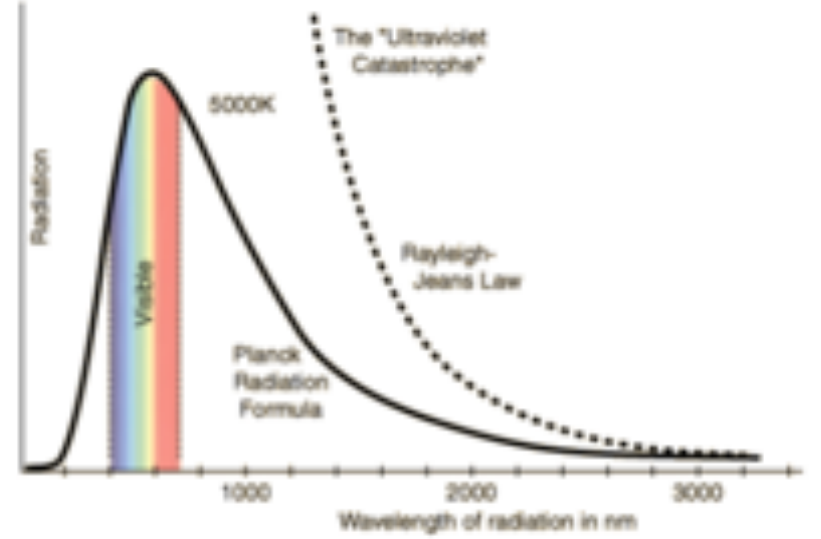
$$\langle E\rangle = \frac{hc}{\lambda(e^{\frac{hc}{\lambda kT}} - 1)}$$

known as the Bose-Einstein Distribution Function.

And the rate of change of energy density with respect to wavelength is [18]:

$$\frac{dU}{d\lambda} = \frac{8\pi hc}{\lambda^{5}(e^{\frac{hc}{\lambda kT}} - 1)}$$

For smaller wavelengths, the law does not predict infinite radiation output and for larger wavelengths, the law aligns with the classical physics derivation of the Rayleigh-Jeans Law [18]. In short, Planck's Law is consistent for all wavelengths of electromagnetic waves. It can also be graphically acknowledged:



Planck's formula solves the inconsistencies of Rayleigh-Jeans Law [24]

The Rayleigh-Jeans Law results in infinite radiation at smaller wavelengths, but Planck's Law creates a smooth curve that works at lower wavelengths as well.

Photoelectric Effect and the Birth of Quantum Physics

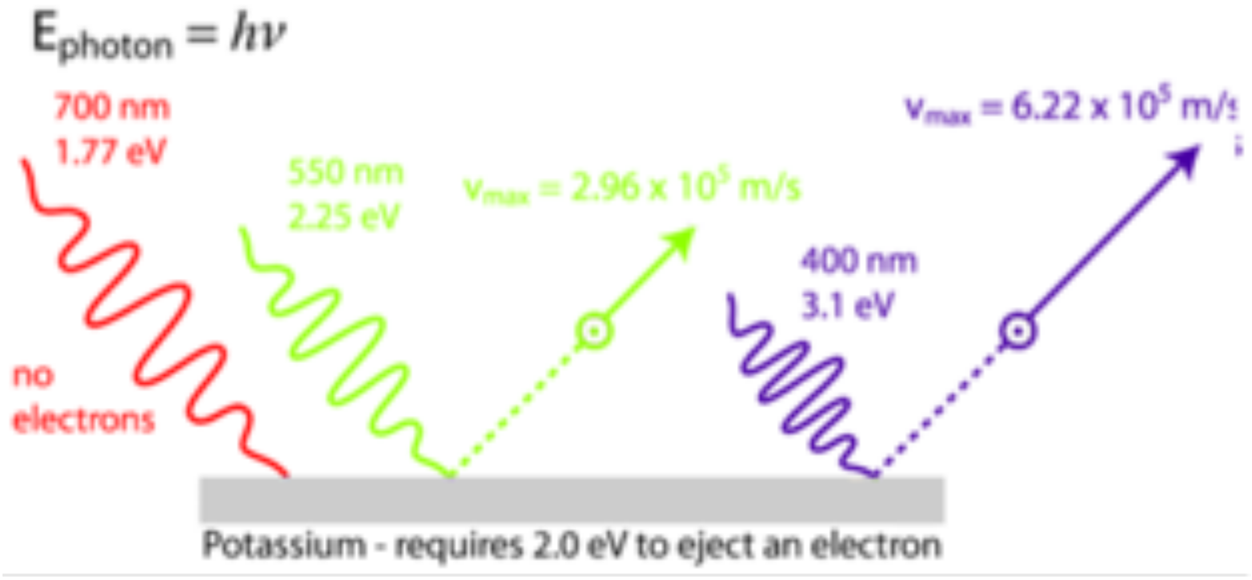
Einstein extended Planck's idea of quanta to light, claiming that a ray of light is just a beam of particles whose energies are correlated to their frequencies as per Planck's Law [26]. He developed the Planck-Einstein Relationship, where one could define a photon, or the particle of light, to have an energy given by:

$$E = \frac{hc}{\lambda} = hv$$

Where v is the photon's frequency. Thus, high frequencies would linearly correlate to high energies.

[The detailed derivation of this formula can be found in Appendix B]

When the beam is directed to the metal and it has a high enough frequency, it will have the energy to kick electrons off the metal and cause a current [26][27].



Depiction of photoelectric effect [27]

For example, in the figure above, Potassium needs at least 2.0 eV to be able to eject an electron and cause a current [27]. The photon of 700 nm red light only has 1.77 eV, so it cannot eject the electron regardless of the light's intensity [27]. On the other hand, the frequencies for both green and purple light are enough to excite an electron into leaving the potassium.

Although the discovery and successful explanation of the photoelectric effect earned Einstein the 1921 Nobel Prize in Physics, his work extended far beyond applications to inducing currents [28].

Wave-Particle Duality

In 1924, Louis de Broglie, a French physicist, extended Einstein's findings by theorizing that all matter, not just light, exhibits properties of both particles and waves [32]. Einstein had developed his famous mass-energy equivalence formula, but de Broglie used it to create De Broglie's Equation:

$$\lambda = \frac{h}{p}$$

Where λ is the wavelength, h is Planck's constant, and p is momentum [32].

This equation was especially significant because it established an inversely proportional relationship between wavelength and momentum. The greater the momentum, the lesser the wavelength (particle-like behavior). And the greater the wavelength, the lesser the momentum (wave-like behavior).

De Broglie's Equation inspired Austrian-Irish physicist Erwin Schrodinger to create the Schrodinger Wave Equation in 1926, solidifying the notion of wave-particle duality by unifying both the wave-like nature and the probabilistic behavior of particles in one working equation [32].

Heisenberg's Uncertainty Principle and the Quantum Cloud Model

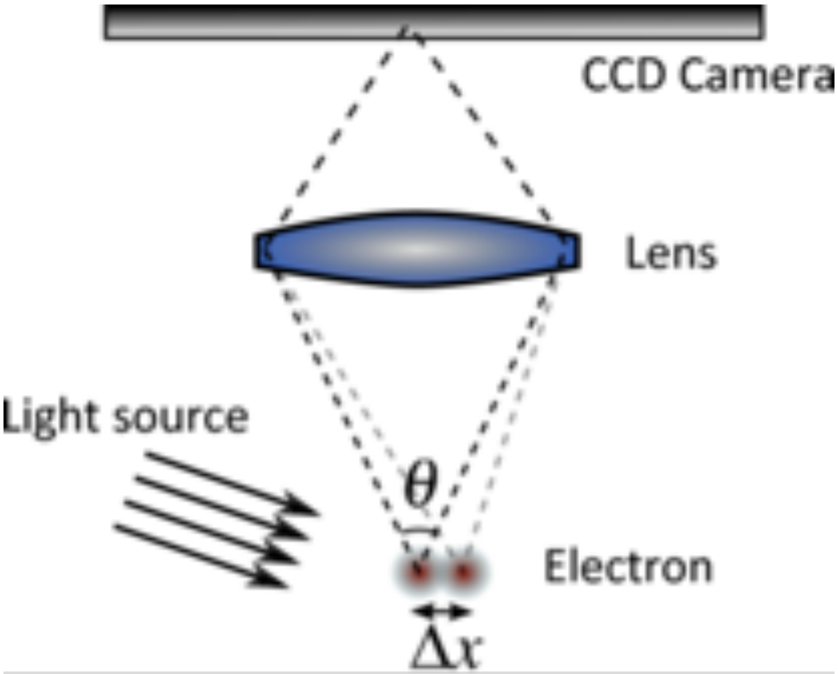
In 1927, physicist Werner Heisenberg challenged the idea of electrons orbiting a nucleus [34].

Heisenberg conducted a famous thought experiment regarding using a gamma ray microscope to measure an electron's position [35]. He stated that a high-energy photon that would be used to illuminate the electron in the microscope would give the electron a boost in energy and unpredictably increase its momentum [35]. The higher the resolution of the microscope, the greater the illuminating photon's energy would be and thus the greater its resultant momentum.

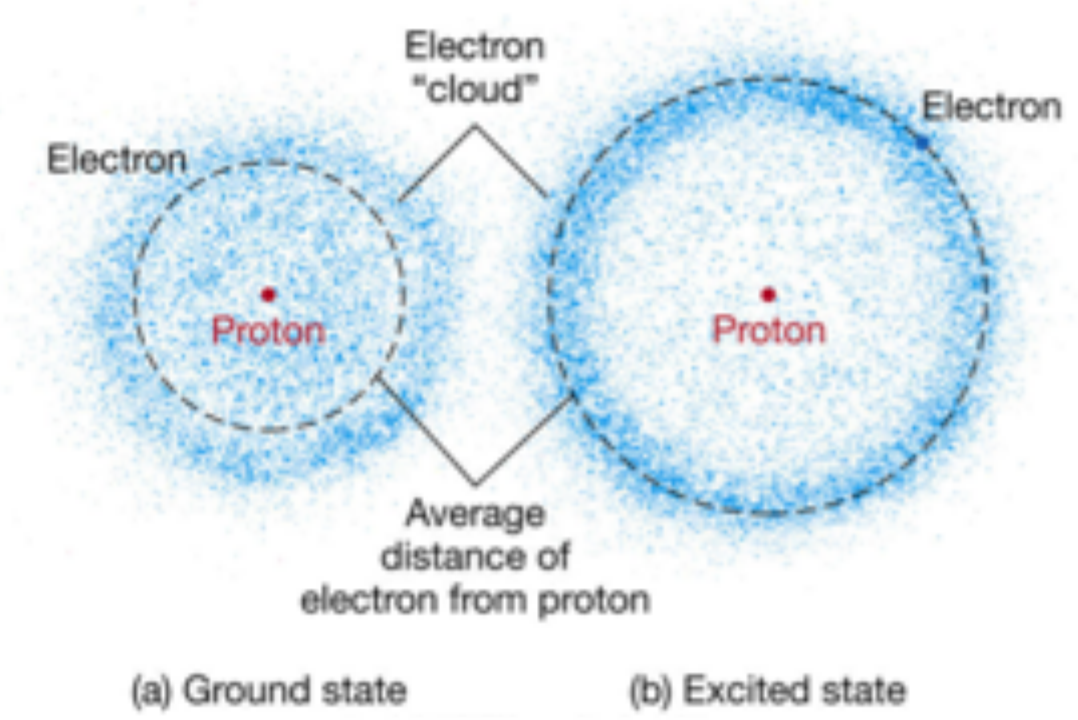
Heisenberg, along with physicist Niels Bohr, stated that this property of uncertainty is fundamental to quantum physics and not just confined to the limitations of instrumentation: it is impossible for physicists to know with complete certainty both the momentum and position of a particle [35].

The inability to determine an electron's position and momentum at a given instant shattered the previous quantum model of electrons neatly orbiting the nucleus, leading to the Quantum Cloud Model [32].

Schrodinger developed an atomic model that doesn't rely on knowing exactly where electrons are. Rather, he described probability fields where the electron is most likely to be found. The three-dimensional cloud spaces signify where electrons have a high probability, 90%, of being found [37]. Thus, the location of an electron can only be given by a generic area where it is likely to be found.



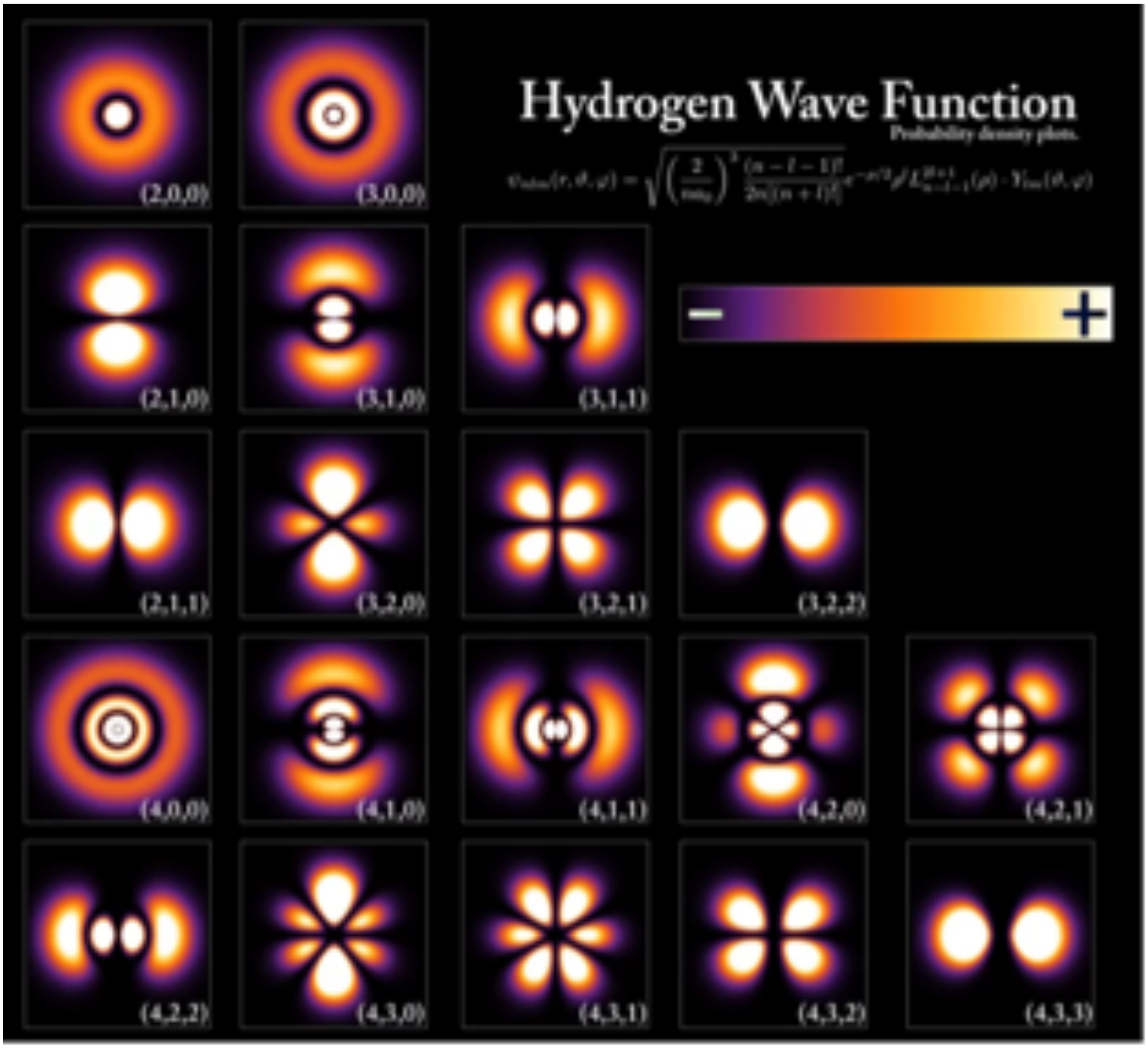
Heisenberg's thought experiment [36]



Ground and excited states of electron clouds [38]

When an electron has more energy, it is in an excited state and is likely farther away from the nucleus. The denser portions of the cloud indicate that the electron is more likely to be found there [38].

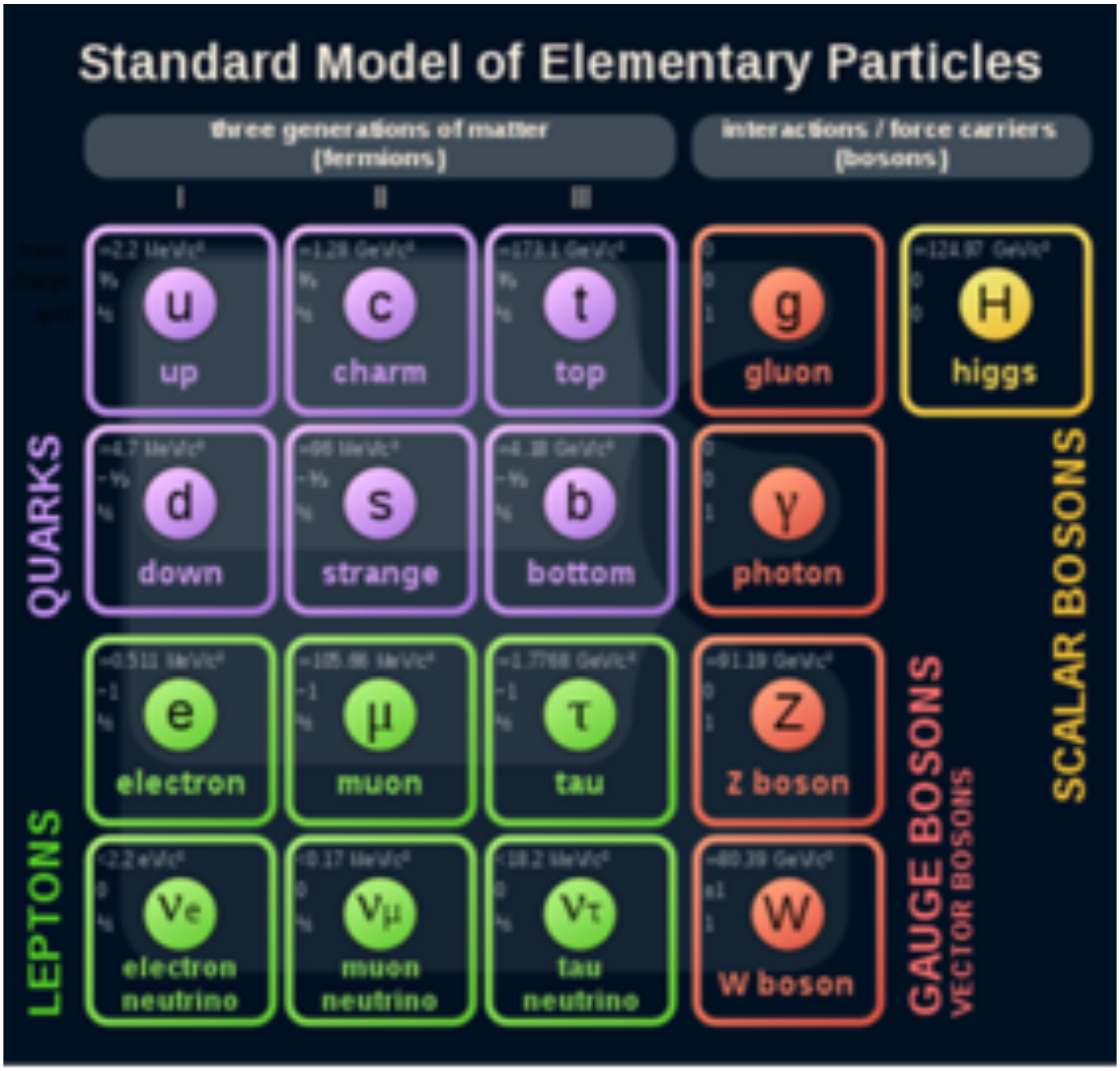
When Schrodinger considered the possibility of several electrons in the atom, he developed the model of electron clouds known today. It replaced orbits with orbitals and used the Schrodinger Wave Equation to describe the shapes of these orbitals [32].



Atomic orbitals of hydrogen [32]

The Standard Model of Particle Physics

The Standard Model is currently the best scientific theory of the foundations of the universe [32][39]. It was formulated by conducting numerous collision experiments in particle accelerators and observing elastic scattering, or analyzing the resultant dynamics through conservation of energy [32][40].

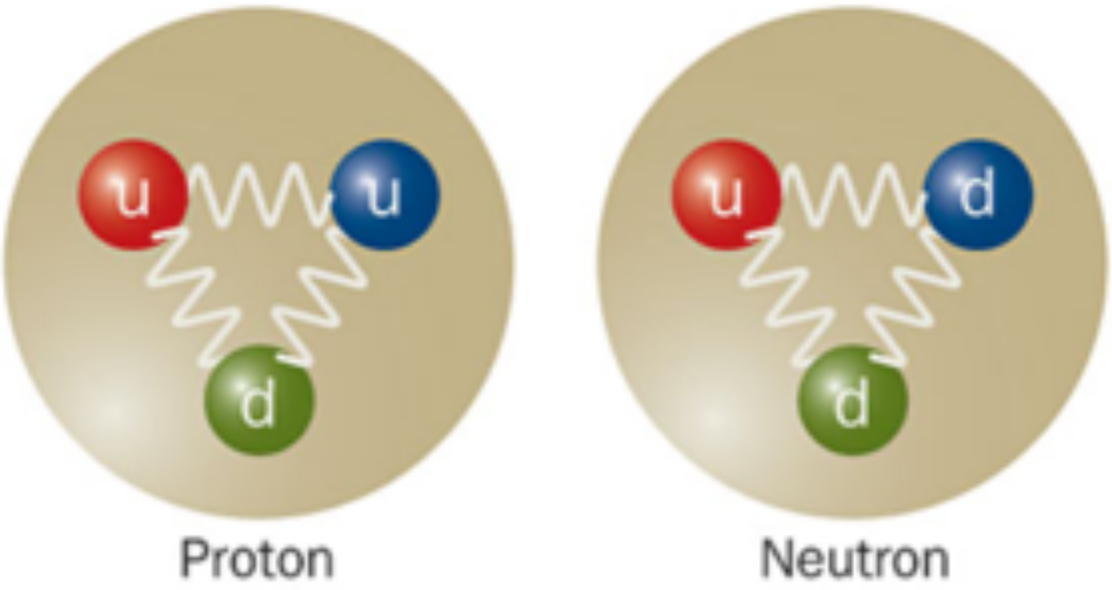


Standard model of particle physics [30]

The model splits the world into two types of particles: fermions and bosons. Fermions are matter particles and bosons are force particles.

Fermions must obey the Pauli Exclusion Principle, which states that no two particles can occupy the same quantum state [41]. In other words, no two fermions can be in the same place at once, as they are the building blocks of matter.

All stable matter in the universe is made up of three fundamental fermions: the electron, up quark, and down quark [43].



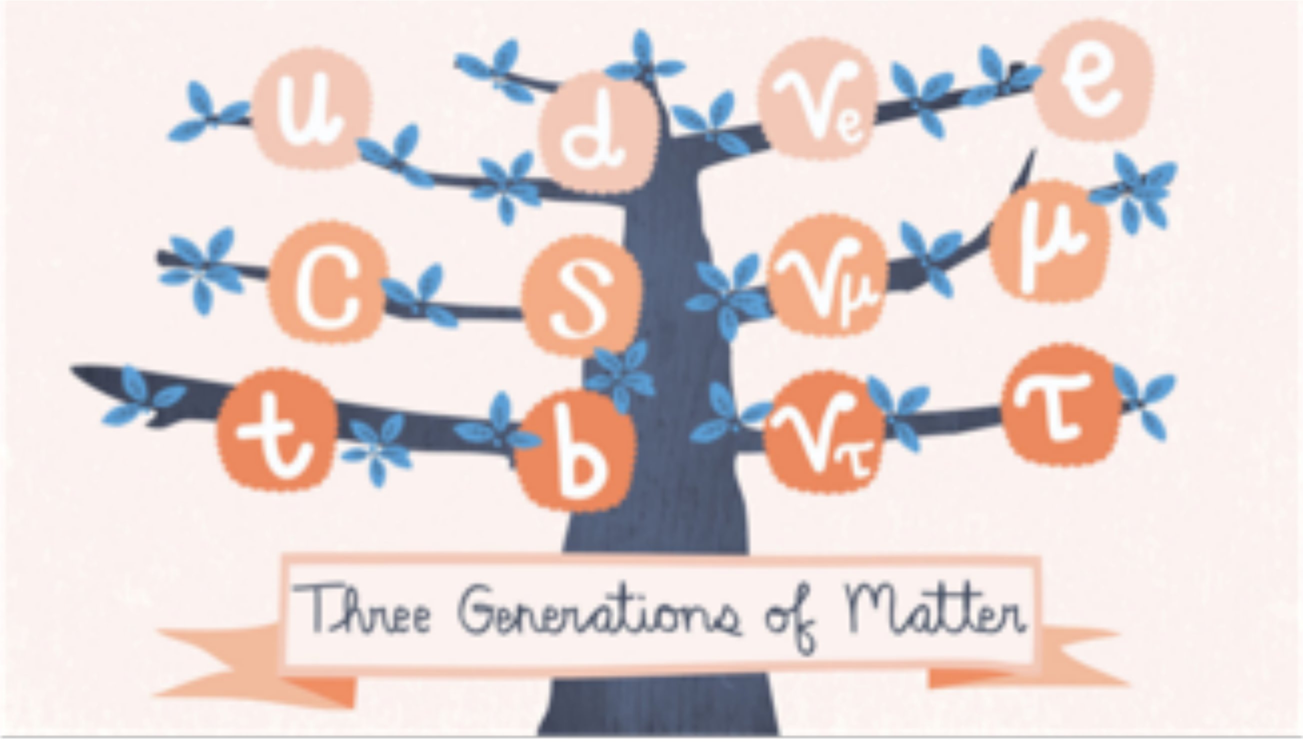
Composition of quarks in nucleons [42]

Two up quarks and a down quark make up a proton and two down quarks and an up quark make up the neutron. Thus, up quarks, down quarks, and electrons from atomic structures that build up our physical reality.

The next type of fermion is the electron neutrino, an extremely weak particle with very little mass [44]. Since neutrinos have no electric charge, they do not contribute to the ionization of matter and were elusive to theoretical physicists for decades [44]. Austrian Physicist Wolfgang Pauli used neutrinos to elucidate the apparent energy loss of radioactively decaying particles [44].

The four matter particles (up quark, down quark, electron, and electron neutrino) form the basis for our model of fermions. The first three make up our world and the fourth is a ghost entity that floats throughout the cosmos.

But for each of these four particles, two more heavier variations also exist. For the up quark, it is the charm and top quarks. For the bottom quark, it is the strange and bottom quarks. For the electron it is the muon and tau particles and for the electron neutrino it is the muon neutrino and the tau neutrinos. Although these eight additional particles exist, they are not seen in everyday life because they are incredibly unstable [43]. These second and third generation particles can be created in a lab, but they quickly decay to the first generation of four basic fermions [45].



Generations of particles in the standard model [46]

Fermions describe matter, but bosons are particles that mediate certain forces, also referred to as force carriers [32]. Unlike fermions, bosons don't have to abide by the Pauli Exclusion Principle and can occupy the same quantum state [32][47]. The Standard Model is effective in describing three of the four fundamental forces of the universe: electromagnetism, the strong force, and the weak force.

Electromagnetism is carried out by interactions with photons, applying a force to any particle that has a charge. The strong force is carried out by gluons that bind protons together in the nucleus of the atom. The weak force exists through the W and Z bosons, and plays a significant role in radioactive decay [32][47].

Lastly, the Higgs boson is a particle that interacts with the Higgs field, an energy field that has the ability to give mass to objects [32]. The Higgs boson generates mass for particles by interacting with this field; lighter objects interact less with the Higgs field and heavier ones interact more [32].

Unfortunately, however, the fourth fundamental force of gravity still remains unexplained in quantum mechanics.

The Need for Quantum Gravity

General relativity has been successful for over a century in describing classical physics [48]. Quantum mechanics has also experimentally and computationally been proven accurate time and time again [49]. The issue arises when both the theories start to disagree with each other. Black holes, predicted by general relativity, should be fully explained by classical physics. But they also have infinitesimally small areas and emit thermal Hawking radiation, so quantum physics should successfully explain black holes too [50].

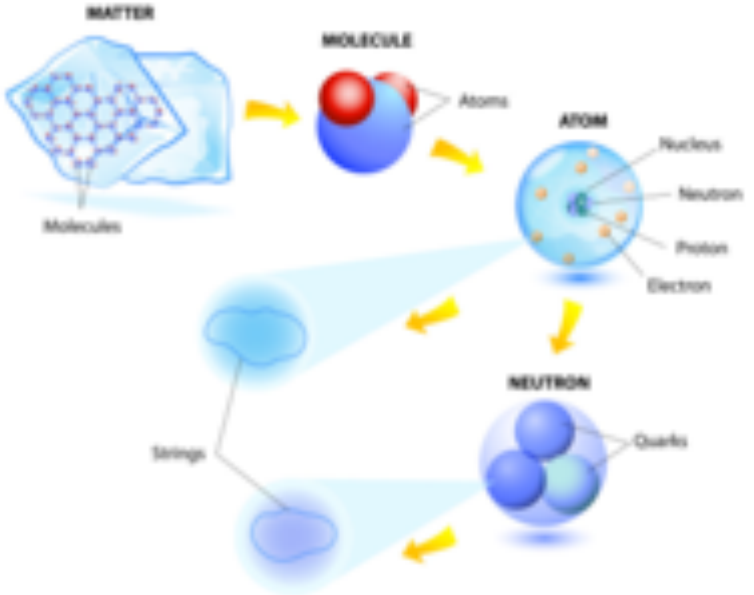
General relativity dictates that objects warp the spacetime around them to create the effect of gravity. But it doesn’t explain how gravity works with a wave function. If a particle behaves as a wave, the issue arises of where and how are its gravitational effects localized. But since the wave has energy or mass, it should still affect gravity. We don’t know how this works because there is no proven model of quantum gravity. General relativity effectively breaks down subatomically, which is concerning because we need to understand quantum gravity to know how its cumulative effects result in general relativity.

The Graviton

Just like how three of the four fundamental forces are mediated through force carrier bosons, it has been a widely acknowledged possibility of there existing a particle to mediate the force of gravity, or the graviton [51]. The problem with gravitons is that each individual particle would be incredibly weak [52]. This makes it incredibly difficult for physicists to detect its presence, and there is no physical evidence of the graviton to this day [51][52].

String Theory

String theory is an attempt to unify all aspects of particle physics and general relativity and still be able to scientifically explain the four fundamental forces [53]. It began with the observation that when elementary particles resonate following their creation in a particle accelerator, they vibrate in regular predictable patterns, such as those of a plucked string [53]. This idea inspired Italian physicist Gabriele Veneziano to propose that subatomic particles are really just small vibrating strings [53][54].



String theory fundamentals [68]

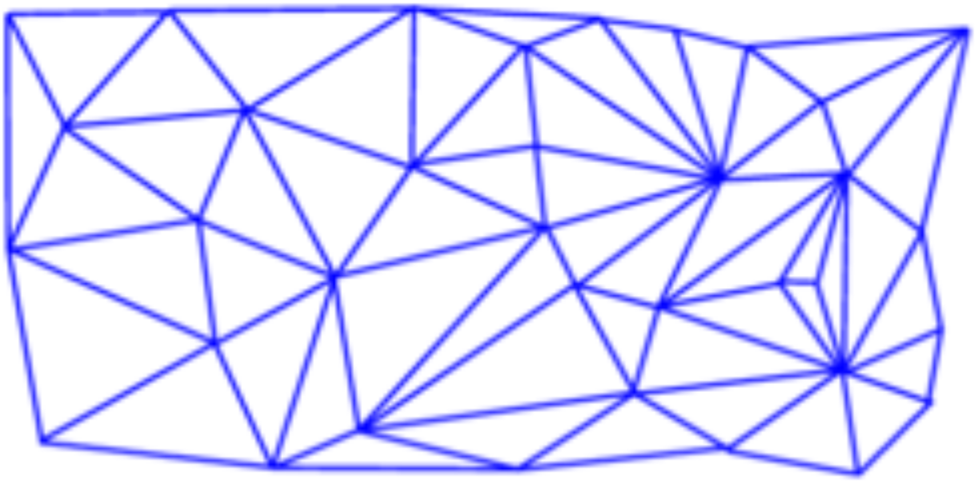
String theory is an ambitious attempt to unify classical and quantum physics; however, its early formulations were based on the assumption that the cosmological constant, which characterizes the expansion of the universe, is negative or zero [55]. Subsequent observational evidence suggested that the constant should be positive due to the accelerated expansion of the universe [56]. This discrepancy led to challenges in reconciling string theory with our understanding of the cosmos [56]. Nevertheless, string theory's theoretical landscape is vast and flexible, allowing researchers to explore newer versions of string theory that incorporate a positive cosmological constant [69]. Testing such theories remains challenging due to the high-energy scales involved and limited scope for experimentation [70].

Loop Quantum Gravity

Loop quantum gravity (LQG) is another approach to a Grand Unified Theory that, unlike string theory which describes the nature of particles in space, describes properties of space-time itself [57]. LQG predicts that upon zooming into the fabric of space-time, one would realize that it is pixelated [58]. There is a minimum possible length, and thus a minimum possible area, and thus a minimum possible volume of space-time [58]. The largest benefit of quantizing space itself is that it removes the idea of singularities [58]. LQG replaces black holes with immensely dense amounts of exotic matter [58]. This removes infinities from equations and replaces them with matter that may be understandable mathematically [58].

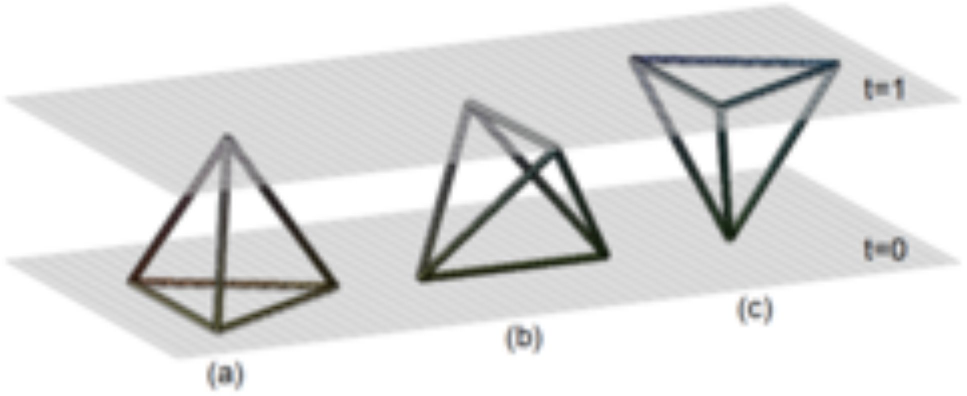
The largest limitation of LQG is that it deals primarily with aspects of space and does not incorporate the variable of time. Although space is quantized, the inability to present time in this theory results in an incomplete representation of 4D spacetime. Some physicists, like Carlo Rovelli, believe that the theory will eventually prove that time is just an emergent characteristic without an existence of its own [64]. LQG still needs significant work, but like string theory, it faces the issue of being immensely difficult to test experimentally [65].

Causal Dynamical Triangulations (CDT)



Triangles forming an instance of space-time [72]

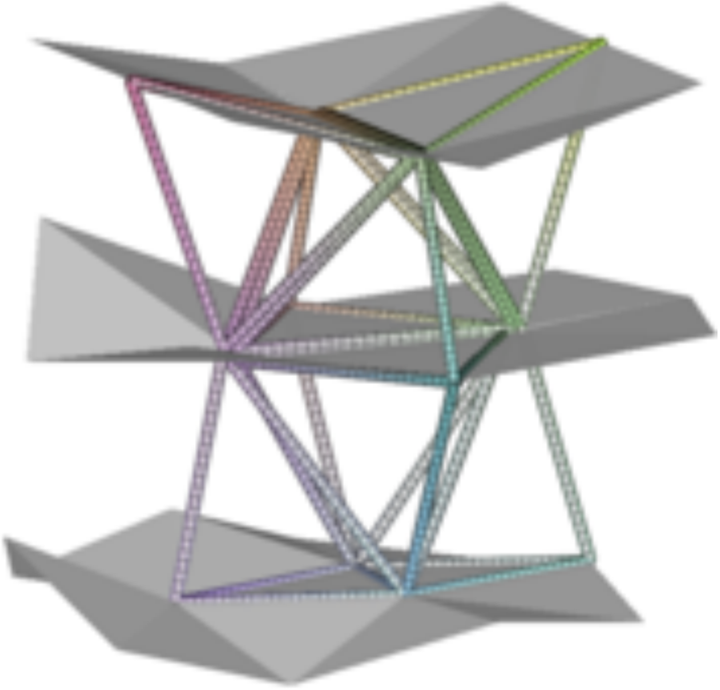
CDT is a quantum gravity theory that solves LQG's limitation of only quantizing space by utilizing triangulations to quantize space-time itself [71]. In CDT, space-time is split up into many flat triangles that can be joined together to create a curvature in spacetime [71]. Each sheet of triangles make up a particular instance of spacetime [71]. Note that each instance of 3D



Types of tetrahedra simplexes in CDT [73] spacetime will be represented as a 2D sheet to allow us to visualize layers of space creating a flow of time.

So far, this is a quantization of space. Space-time is quantized through geometric chunks called simplexes that serve as building blocks to connect one instance of spacetime to another [71][72]. For a 4D space-time that is represented as 3D, there are three types of simplexes. The image above depicts these three possible orientations. Tetrahedra are labeled by the number of vertices on each time slice so (a) is a (3,1)-tetrahedron because it has 3 vertices on t=0 and 1 on t=1 [73]. Similarly, (b) is a (2,2)-tetrahedron and (c) is a (1,3)-tetrahedron [73].

When we put all the tetrahedra face to face and edge to edge, while making sure to eliminate all gaps, we end up with something like the image on the right [73]. The gray foils are portions of spatial slices at particular times [73]. In 3D, it is apparent that the simplexes are able to make up a curvature in space-time at each instance of time.



Chunk of space-time in Causal Dynamical Triangulations [73]

CDT is particularly useful because researchers may investigate simplexes at different instances of times. For example, a tetrahedron at one instance may be macroscopic and would follow the known theory of general relativity, but at a different time frame, the tetrahedron may converge to a microscopic shape that is more aligned with quantum physics. By examining these connections, scientists seek to understand the fundamental nature of gravity at the quantum level.

One of CDT's main limitations include that it requires enormous computational complexity to form models of the universe linking initial and final states [73]. The challenge arises from the sheer number of possible triangulations that can be used to construct each lattice. As the lattice becomes larger or involves higher-dimensional space-time, it becomes computationally intractable. Until recently, it has only been possible to simulate empty universes through CDT, or otherwise the results looked like "crumpled" geometries that do not reflect our universe [73][74]. But researchers are working on models that incorporate matter as well and are starting to obtain reasonably classical space-time models [73][74].

Current AI Research Initiatives

Despite extreme difficulties in experimentally testing quantum theories of gravity and mathematically handling the multitude of variables involved, researchers are continuously exploring newer methods to understand quantum gravity. Emerging technologies like AI offer a promising avenue to tackle these formidable challenges and continue exploring quantum gravity.

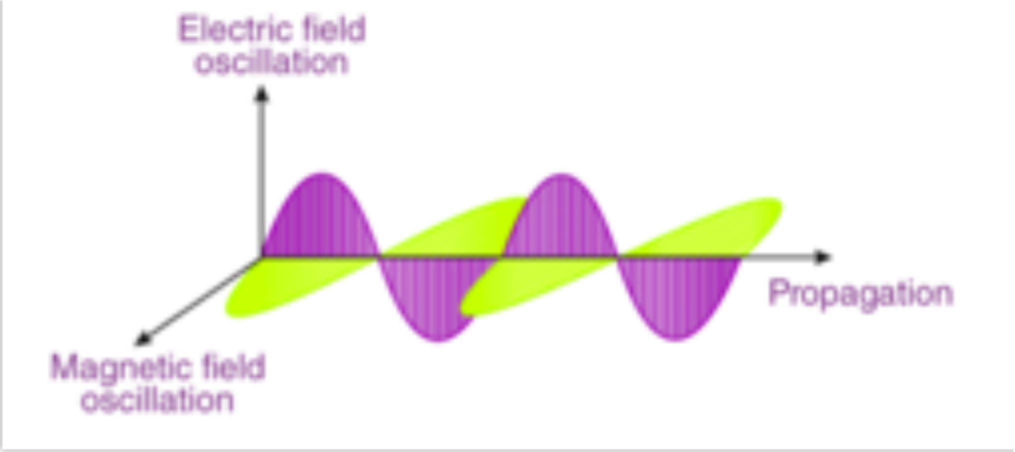
AI has already proven itself useful in quantum mechanics. Particle physics frequently results in large sets of complex formulas that are difficult to simplify. The Hubbard model is used in solid-state physics to describe the behavior of grouped sets of electrons [59]. Computationally, it gets complex when quantum entanglement is considered [60]. When some electrons interact even once, their resultant states may no longer be independent of each other, regardless of how far apart they are afterwards [60]. When more electrons are introduced in the system, more quantum entanglements need to be accounted for and the computation becomes exponentially more difficult [60]. Utilizing a machine learning algorithm that ran for several weeks, researchers simplified a 100,000-equation physics conundrum to just four equations, exemplifying how AI may be the future of quantum exploration [60].

A team from MIT is using machine learning to explore fundamental forces and particle physics [61]. Assistant Professor of Physics Phiala Shanahan stated, “There are a lot of interesting problems that we know how to address in principle, but we just don’t have enough compute, even though we run on the largest supercomputers in the world” [61]. By pushing past computational limitations with machine learning, Shanahan is developing models of particle dynamics by leading a team in developing AI simulations.

String theory predicts that there are many extra dimensions folded in our reality and a large number of possible manifolds depicting this [62]. Northeastern University Assistant Professor of Physics James Halverson is using data science and machine learning to narrow down on the mathematical models of the universe and interpret their implications [62][63].

There is no current model of physics that completely unifies quantum mechanics and general relativity, but advances in machine learning and development of newer theories of quantum gravity are bound to result in the Grand Unified Theory that scientists have been looking for.

Appendix A: Derivation of Rayleigh-Jeans Law



Depiction of electromagnetic waves [31]

In a closed system at equilibrium with its surroundings, electromagnetic standing waves must obey the three-dimensional scalar wave equation [18][76]:

$$\nabla^2\Psi = \frac{\partial^2\Psi}{\partial x^2} + \frac{\partial^2\Psi}{\partial y^2} + \frac{\partial^2\Psi}{\partial z^2} = \frac{1}{c^2}\frac{\partial^2\Psi}{\partial t^2}$$

This wave equation should be solved with a certain boundary condition: that the amplitude of the wave must be zero at the cavity walls. Otherwise, the energy of the wave may leak out and the system would no longer be closed and isolated [76]. The boundary conditions can be met with a solution of the following generic form [76]:

$$E = E_0 sin(\frac{n_1\pi x}{L})sin(\frac{n_2\pi y}{L})sin(\frac{n_3\pi z}{L})sin(\frac{2\pi ct}{\lambda})$$

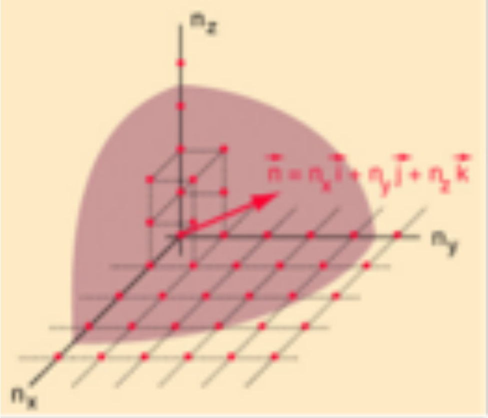
Substitution back into the 3D wave equation yields:

$$(\frac{n_1\pi}{L})^2 + (\frac{n_2\pi}{L})^2 + (\frac{n_3\pi}{L})^2 = (\frac{2\pi}{\lambda})^2$$

Then simplify. Thus, standing waves in a closed cavity must obey the following equation [18]:

$$n_1^2 + n_2^2 + n_3^2 = \frac{4L^2}{\lambda^2} \quad (1)$$

for which L is the length of the isolated cubical cavity, λ is the wavelength, and n_1, n_2, and n_3 are the number of waves in the x, y, and z directions respectively [18].



Rayleigh scheme for counting modes [76]

A wave mode is a specific configuration in which a wave oscillates in a system [75]. We need to consider every possible mode that meets equation (1), so we construct an ellipsoid. The volume of this shape will provide a good approximation of all possible combinations of n values [18].

Note that we only consider ⅛ of the ellipsoid because the solution to the wave equation only uses positive values and so we just consider the shape's volume in one quadrant.

$$\text{Volume of n's} = \frac{1}{8} \cdot \frac{4\pi}{3} (n_1^2 + n_2^2 + n_3^2)^{3/2}$$

We will also consider that waves may be polarized in perpendicular planes (since the electric and magnetic fields oscillate perpendicularly), so the number of wave possibilities should be multiplied by 2 [18].

$$\text{Number of modes of } n\text{'s} = \text{N} = 2 \cdot \frac{1}{8} \cdot \frac{4\pi}{3} (n_1^2 + n_2^2 + n_3^2)^{3/2}$$

Plugging in equation (1):

$$\text{N} = 2 \cdot \frac{1}{8} \cdot \frac{4\pi}{3} (n_1^2 + n_2^2 + n_3^2)^{3/2} = 2 \cdot \frac{1}{8} \cdot \frac{4\pi}{3} (\frac{4L^2}{\lambda^2})^{3/2} = \frac{8\pi L^3}{3\lambda^3}$$

To find how the number of modes changes in relation to wavelength, we differentiate with respect to wavelength:

$$\frac{dN}{d\lambda} = \frac{d}{d\lambda}\left(\frac{8\pi L^3}{3\lambda^3}\right) = -\frac{8\pi L^3}{\lambda^4}$$

The negative sign implies that when wavelength increases, the number of modes will decrease. In order to find the number of modes N per unit volume per unit wavelength, divide both sides by the volume of the cubical cavity (L was each cube's length so L^3 is the volume of each cell) [76]:

$$\frac{(Nodes\ per\ unit\ wavelength)}{(Cavity\ volume)} = -\frac{1}{L^3}\frac{dN}{d\lambda} = \frac{8\pi}{\lambda^4}$$

Note that the negative sign is moved to the other side because the number of nodes cannot be negative.

The principle of equipartition of energy states that energy is shared equally between the different degrees of freedom, or modes [19]. Additionally, the average energy per mode is kT (k is Boltzmann's constant and T is temperature in Kelvin) [18]. If E is the energy and U represents the energy density, $\frac{dU}{d\lambda}$ is the rate of change of energy density with respect to wavelength:

$$\frac{dU}{d\lambda} = \frac{dE}{d\lambda L^3} = kT\left(-\frac{1}{L^3}\frac{dN}{d\lambda}\right) = kT\frac{8\pi}{\lambda^4} = \frac{8\pi kT}{\lambda^4}$$

This result was used in the Rayleigh-Jeans Law and led to the Ultraviolet Catastrophe [18][76]. When frequencies are low (making wavelengths high), the formula produces reasonable approximations [76]. But when frequencies are high (and wavelengths are low), the Planck radiation formula must be used instead [76].

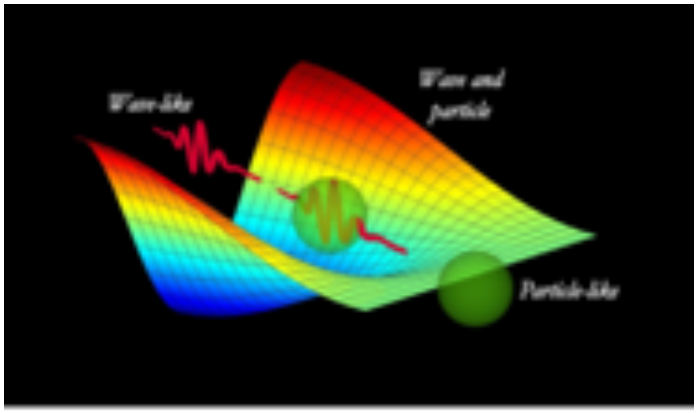
Appendix B: Derivation of de Broglie's Equation

Start off with Einstein's energy-matter equivalence equation:

$$E = mc^2$$

Where E is energy, m is mass, and c is the speed of light.

According to Planck's theory, each quantum of a wave carries a discrete amount of energy represented by the Planck-Einstein Relationship [77]:



Wave-particle duality [79]

$$E = hv$$

Where E is energy, h is Planck's constant, and v is the frequency of the wave.

De Broglie believed that particles and waves possess the same traits, so he set the two energy formulas equal to each other and substituted velocity for the speed of light [77][78]:

$$mv^2 = hv$$

He then substituted $\frac{v}{\lambda}$ for v because $v = \frac{c}{\lambda}$, and now v and c are being equated [77]:

$$mv^2 = h\frac{v}{\lambda}$$

With some shuffling around, we arrive at de Broglie's Equation:

$$\lambda = \frac{h}{mv} = \frac{h}{p}$$

Where λ is the wavelength, h is Planck's constant, and p is momentum [32].

Sources

1. https://mathshistory.st-andrews.ac.uk/Biographies/Ptolemy/
2. https://www.khanacademy.org/humanities/big-history-project/big-bang/how-did-big-bang-change/a/claudius-ptolemy
3. https://apod.nasa.gov/apod/ap100613.html
4. https://astronavigationdemystified.com/the-retrograde-and-prograde-motions-of-mars-and-jupiter/
5. http://www.faithfulscience.com/science-and-faith/brief-history-of-faithful-science.html
6. https://earthobservatory.nasa.gov/features/OrbitsHistory
7. https://www.cs.mcgill.ca/~rwest/wikispeedia/wpcd/wp/p/Philosophiae_Naturalis_Principia_Mathematica.htm
8. https://www.space.com/17661-theory-general-relativity.html
9. https://www.discovermagazine.com/the-sciences/how-to-understand-einsteins-theory-of-gravity
10. https://www.esa.int/ESA_Multimedia/Images/2015/09/Spacetime_curvature
11. https://gizmodo.com/the-200-year-old-mystery-of-mercurys-orbit-solved-1458642219
12. https://www.ck12.org/physics/Orbital-Motion/rwa/Mercurys-Orbit/
13. https://socratic.org/questions/why-is-there-perihelion-and-aphelion-of-a-planet-s-orbit
14. https://griffithobservatory.org/explore/observing-the-sky/whats-in-the-sky/eclipses/
15. https://www.forbes.com/sites/startswithabang/2019/05/29/this-is-how-100-years-ago-a-solar-eclipse-proved-einstein-right-and-newton-wrong/?sh=4bac26361610
16. https://news.uchicago.edu/explainer/black-holes-explained
17. https://www.astronomy.com/magazine/ask-astro/2019/09/how-does-gravity-affect-photons-that-is-bend-light-if-photons-have-no-mass
18. https://eng.libretexts.org/Bookshelves/Materials_Science/Supplemental_Modules_(Materials_Science)/Electronic_Properties/Solving_the_Ultraviolet_Catastrophe
19. https://aklectures.com/lecture/first-law-of-thermodynamics/principle-of-equipartition-of-energy
20. https://unacademy.com/content/neet-ug/study-material/physics/the-rayleigh-jeans-radiation-law/
21. https://www.britannica.com/video/185533/Max-Planck-origin-quantum-theory
22. https://bigthink.com/13-8/max-planck-birth-quantum-physics/
23. https://physics.stackexchange.com/questions/116302/how-is-temperature-related-to-color
24. https://www.researchgate.net/figure/Rayleigh-Jeans-and-Plancks-Curve-21_fig5_44254541
25. https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/The_Live_Textbook_of_Physical_Chemistry_(Peverati)/16%3A_The_Motivation_for_Quantum_Mechanics/16.03%3A_The_Ultraviolet_Catastrophe
26. https://www.aps.org/publications/apsnews/200501/history.cfm
27. https://chem.libretexts.org/Courses/University_of_Arkansas_Little_Rock/Chem_1402%3A_General_Chemistry_1_(Kattoum)/Text/6%3A_The_Structure_of_Atoms/6.2%3A_Quantization%3A_Planck%2C_Einstein%2C_Energy%2C_and_Photons
28. https://www.nobelprize.org/prizes/lists/all-nobel-prizes/
29. https://www.amnh.org/exhibitions/einstein/legacy/quantum-theory
30. https://plus.maths.org/content/charmed-beauty-confirms-particle-theory

31. https://byjus.com/physics/electromagnetic-waves/
32. https://www.evincism.com/history-development-of-particle-physics-and-the-standard-model/
33. https://earthsky.org/human-world/einsteins-most-famous-equation-emc2/
34. https://scienceexchange.caltech.edu/topics/quantum-science-explained/uncertainty-principle
35. https://www.aps.org/publications/apsnews/200802/physicshistory.cfm
36. https://www.researchgate.net/figure/Heisenbergs-Microscope-oers-an-intuitive-origin-for-the-uncertainty-relationship-A_fig1_253929537
37. https://chem.libretexts.org/Bookshelves/Introductory_Chemistry/Introductory_Chemistry_(CK-12)/05%3A_Electrons_in_Atoms/5.11%3A_Quantum_Mechanical_Atomic_Model
38. https://www.universetoday.com/38282/electron-cloud-model/
39. https://www.energy.gov/science/doe-explainsthe-standard-model-particle-physics
40. https://galileoandeinstein.phys.virginia.edu/7010/CM_16_Elastic_Scattering.html
41. https://byjus.com/jee/pauli-exclusion-principle/
42. https://www.sciencenews.org/article/standard-model-gets-right-answer-proton-neutron-masses
43. https://home.cern/science/physics/standard-model
44. https://www.britannica.com/science/neutrino
45. https://www.particleadventure.org
46. https://www.symmetrymagazine.org/article/august-2015/the-mystery-of-particle-generations
47. http://hyperphysics.phy-astr.gsu.edu/hbase/Particles/spinc.html
48. https://www.scientificamerican.com/article/einsteins-greatest-theory-just-passed-its-most-rigorous-test-yet/
49. https://www.advancedsciencenews.com/standard-model-tested-with-record-breaking-accuracy/
50. http://www.scholarpedia.org/article/Hawking_radiation
51. https://www.news.ucsb.edu/2020/019817/hunt-gravitons
52. https://www.scientificamerican.com/article/is-gravity-quantum/
53. https://www.infoplease.com/math-science/space/universe/theories-of-the-universe-a-brief-history-of-string-theory
54. https://encyclopedia.pub/entry/37553
55. https://medium.com/starts-with-a-bang/why-string-theory-is-both-a-dream-and-a-nightmare-20f47fe6e99a
56. https://ned.ipac.caltech.edu/level5/Carroll2/Carroll2_2.html
57. https://www.quantamagazine.org/string-theory-meets-loop-quantum-gravity-20160112/
58. https://www.space.com/loop-quantum-gravity-space-time-quantized
59. https://arxiv.org/abs/2103.12097
60. https://www.sciencedaily.com/releases/2022/09/220926114753.htm
61. https://physics.mit.edu/news/provably-exact-artificial-intelligence-for-nuclear-and-particle-physics/
62. https://news.northeastern.edu/2019/08/05/how-theoretical-physicist-james-halverson-is-using-data-science-and-machine-learning-to-study-string-theory/
63. https://cos.northeastern.edu/people/james-halverson/

64. https://www.dummies.com/article/academics-the-arts/science/physics/benefits-and-flaws-of-loop-quantum-gravity-177740/#:~:text=The%20biggest%20flaw%20in%20loop,space%2Dtime%20out%20of%20it.
65. https://phys.org/news/2012-01-physicists-loop-quantum-gravity.html
66. https://selfstudypoint.in/black-body-radiation/
67. https://www.khanacademy.org/science/ms-physics/x1baed5db7c1bb50b:waves/x1baed5db7c1bb50b:wave-properties/a/wave-properties
68. https://kidspressmagazine.com/science-for-kids/misc/misc/string-theory.html
69. https://arxiv.org/abs/hep-th/0105151
70. https://www.space.com/putting-string-theory-to-test.html#:~:text=A%20perturbing%20problem&text=The%20strings%20of%20string%20theory,with%20our%20most%20precise%20instruments.
71. https://web2.ph.utexas.edu/~coker2/index.files/CDT-CS.htm
72. https://arxiv.org/pdf/1307.5469.pdf
73. https://www.thephysicsmill.com/2013/10/13/causal-dynamical-triangulations/
74. https://phys.libretexts.org/Bookshelves/Astronomy__Cosmology/Supplemental_Modules_(Astronomy_and_Cosmology)/Cosmology/Carlip/Causal_Dynamical_Triangulations
75. https://www-personal.umd.umich.edu/~jameshet/IntroLabs/IntroLabDocuments/150-12%20Waves/Waves%209.0.pdf
76. http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/rayj.html#c3
77. https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_(Physical_and_Theoretical_Chemistry)/Quantum_Mechanics/02._Fundamental_Concepts_of_Quantum_Mechanics/Deriving_the_de_Broglie_Wavelength
78. https://www.vedantu.com/question-answer/derive-debroglies-equation-class-11-chemistry-cbse-5f4e72fcd1fa823ca5939530
79. https://www.livescience.com/24509-light-wave-particle-duality-experiment.html