Newton vs. Einstein: Action at a Distance and Field Theory

Class 1 23-119 One Choi
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In this unit, we begin with the story of Newton and Einstein, who challenged him. Newton deserves to be praised as the greatest physicist of his time, in that he devised the “unprovable” physical axioms of classical physics. Einstein, however, refuted all of Newton’s physical laws that had been believed to be true, and these refutations were experimentally demonstrated. This placed the two geniuses into a confrontational relationship. Einstein’s papers on his most basic ideas of time and space, the principle of universal gravitation and action at a distance, and the nature of light all dismantled the achievements built by Newton. Since this book deals with the decisive moment in which the theory of relativity was born, it was essential to discuss the confrontation between Newton and Einstein, and necessary to deal in detail with Newton’s physical laws, which form the basis of physics.

It is widely known that Newton laid the foundations of physics and mathematics, but this is partly a myth containing exaggeration. Memoirs describe Newton as having systematically studied and researched in his youth, but when compared with reality, suspicious points appear. Newton is also known as the inventor of calculus. However, this is difficult to see as purely his own idea and research. Methods such as fluxions and the Taylor series had already been published. Newton obtained the idea of calculus from his teacher Barrow, generalized it, and established various theorems. It is undeniable that he was extremely intelligent and bright, but not all of calculus, physical axioms, and papers on universal gravitation were solely Newton’s contributions.

Newton’s first law of motion states that a body not acted upon by an external force maintains its velocity (speed + direction). The discussion of force also appears in the second law of motion. At this point, Newton’s laws of motion introduce the ambiguous concepts of “force” and “mass.” Defining these two concepts is extremely difficult both physically and philosophically. In the formula F=ma, what appears on the left-hand side is “force.” In everyday life, when we speak of “force,” we may think of power or strength, but in physics, force has a different meaning. Force can be interpreted in four representative ways.

The first interpretation presupposes the reality of “force” and “mass” and interprets the formula as expressing the relation between these two realities. In this case, force can be seen as the cause that accelerates a mass-bearing body, and if force is applied, the body acquires acceleration as a relation between the two real entities. This interpretation is the one currently accepted.

The second interpretation simply defines force as the product of mass and acceleration, thereby eliminating the concept of force. In this way, F is ma, and solving the equation of motion means finding the relations among mas. This has the advantage of not requiring a difficult definition of force.

The third interpretation sees force as the result of the motions of the particles that constitute a body. If one interprets force in terms of the motions of constituent particles, the concept of force can be simplified into particle motion and reduced to what is already known. Of course, this does not mean eliminating the concept of force.

Finally, the fourth interpretation seeks to define mass in terms of force. René Descartes wanted to explain the motion of mass only by applied force and resisting force. Thus, he regarded only the interactions of forces as real.

Although such rigorous and difficult interpretations exist, anti-realists argue that F=ma should be accepted only as a tool for describing phenomena, used for its utility, without requiring philosophical interpretation. Newton's laws of motion already have sufficient value as tools for explaining natural phenomena.

Newton's laws of motion, which can admit multiple interpretations, in fact have a remarkable difference from other physical laws. Ohm's law, Hooke's law, Kepler's laws of planetary motion, Gauss's law—physics has produced countless physical laws, which allow more accurate understanding of the relations between physical quantities. However, the reason Newton's laws stand out among these many laws is that they cannot be proven. Newton's laws of motion are axioms, the basic principles of all macroscopic natural phenomena. By constructing an axiomatic system of physics, Newton derived the more specific physical laws mentioned above.

However, Newton could not explain the principle of universal gravitation. Two mass-bearing bodies are said to have an attractive force inversely proportional to the square of their distance, but intuitively this seemed very strange. For when only two bodies are considered, they have no consciousness and cannot be thought to exchange information. At this point, Newton attempted to explain it by introducing an invisible substance called the aether, but Faraday sought to explain it by what is commonly called a "field." He argued that it is not that a body or charge is placed and then a field is formed, but that the field is first formed, and bodies are situated according to it, and that through the field universal gravitation acts and interaction occurs.

Another ambiguous concept that then appeared is "mass." Mass can be defined as the "intrinsic quantity of a body." However, if one hearing this definition for the first time were asked to measure the mass of a schoolbag immediately, they would be perplexed. The etymology and origin of the word are also mysterious. "Quality" and "quantity" usually have opposing meanings, but in the 18th century, a scholar of Dutch learning, when translating into Chinese characters, simplified "quantity of matter" into the compound word "mass."

As an alternative definition, mass can be matched with inertia, that is, "the degree to which a body tends to maintain its original state of motion." In fact, the larger the mass of an object, the harder it is to stop its motion. From a classical standpoint, defining it in this way does not cause major problems, but with the development of Einstein's theory of relativity, difficulties arise. According to Einstein's principle of mass-energy equivalence, $E_0=m_0c^2$. That is, mass and energy are equivalent. However, energy cannot be matched with inertia. If physics is extended to general relativity, then the gravitational field has energy, making it extremely difficult to assign a clear single definition to mass.

Newton's laws of motion were not born simply from Newton's deep contemplation, but are interwoven with various historical stories, and contain many concepts that are philosophically hard to define. While not knowing these concepts does not hinder solving physics problems, it allows a broader understanding of physics.

Question: Faraday regarded "lines of force" or "fields" as fundamental entities, and particles as knots or nodes of those fields. That is, the field is born first, and particles are born in accordance with such a field. How is this possible? I am curious about Faraday's interpretation of the interaction between fields and particles.

Seminar: What is Space?

Class 1 23-119 One Choi
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Introduction

In daily life, space can generally be defined simply. Space is an intuitive concept for people living in 3(+1) dimensions, and can be easily defined through concepts such as coordinates, distance, and size. However, philosophically and physically, defining space is very cumbersome and inconvenient. It is necessary to carefully examine whether space exists independently, or whether it is a concept derived through some relation, or even further, whether space does not exist at all and is defined merely as a tool for calculation.

A representative figure who discussed space in ancient times is Aristotle. Aristotle explained space through the relational theory with the universe. He argued that space is defined through the location occupied by an object and its relation to surrounding matter, and is not an independently existing substance. The idea of space had a significant influence even during the Scientific Revolution.

Newton, Leibniz, and Galileo's Space-Time

Descartes, a representative figure of the Scientific Revolution, claimed that matter is space, and further, that space is merely an extension of matter. Space exists because matter exists, and thus he did not acknowledge a vacuum where no matter exists. Based on this, Descartes created a three-dimensional orthogonal coordinate system, which Newton extensively used to mathematically establish his concepts of absolute space and absolute time.

Leibniz was a physicist who first argued that the existence of absolute space was unnecessary. To Leibniz, space was the relational arrangement between objects. One can imagine the following situation: the arrangement of certain objects can be called "World 1," and if this arrangement is moved sideways identically, it can be called "World 2." According to the Principle of Identity of Indiscernibles (PII), the two worlds cannot be distinguished. Absolute space is homogeneous and isotropic, so physical laws apply identically at any point in space, making PII hold. However, Leibniz asserted the Principle of Sufficient Reason (PSR) here. If Newton's absolute space exists, PII would apply to "World 1" and "World 2," and there would be no way to distinguish the two worlds, violating PSR. In other words, there is no reason to choose a particular world, and absolute space need not exist. Thus, Leibniz claimed that space is formed in the relations between objects.

Before proceeding, it is necessary to discuss Leibniz's Principles of Sufficient Reason and Identity of Indiscernibles more concretely. The Principle of Sufficient Reason states that for any event to occur or for something to exist, there must necessarily be a sufficient reason for it. In other words, there is no effect without a cause. Using this, Leibniz argued that results without definite causes or reasons are meaningless. In the above example, since there is no way to distinguish the two worlds, there is no reason to select one of them. The Principle of Identity of Indiscernibles concerns two worlds that cannot be distinguished. Specifically, if two objects cannot be logically distinguished, they are in fact identical. For example, $\sqrt{4}$ and 2 cannot be logically distinguished, so they are considered equal. Leibniz used this logic to later refute Newton's disciple Clarke's arguments regarding absolute velocity.

Leibniz also refuted Newton's concept of absolute time. Leibniz claimed that time is also relational among matter. In a world where objects exist, events occur. For example, if there are only two particles, the moment they collide or the moment they exceed a certain distance can be considered an event. This series of events shows order, and Leibniz considered time simply as the collection of these events. However, if one imagines an empty space without matter, no events would occur locally, and in that case, the temporal order of events would not exist, making the concept of time meaningless.

As mentioned earlier, for Newton, time and space were absolute. The thought experiment used to prove this and refute Leibniz's theory involved a bucket. Imagine an ideal bucket suspended by a rope or with a rotating plate below (without a handle). If water fills half of the bucket and it is spun, initially only the bucket rotates at a constant angular velocity. Over time, the water gradually begins to rotate until eventually it matches the bucket's angular velocity. As the water rotates, the water near the rotation axis becomes concave, and the water level rises in a parabolic shape farther from the axis.

Newton thought that rotational motion does not occur spontaneously, but must rotate with respect to some absolute reference. Here, the bucket and water rotate at the same angular velocity, so there is no relative motion between them, but by observing the shape of the water surface, one can clearly say that the water is rotating. Therefore, the water rotates with respect to an absolute reference, which is absolute space.

Newton proposed another thought experiment using two spheres and a cord to demonstrate absolute space. Imagine two spheres connected by a cord. If the spheres rotate, tension arises in the cord to produce centripetal force. Newton claimed that this tension is physical evidence of rotation, and that rotation is possible with respect to absolute space. Similar to the bucket experiment, the spheres do not move relative to each other, so they are rotating with respect to absolute space.

The argument over absolute space and time continued with Newton's disciple Clarke, who engaged in the debate on absolute velocity. Newton, supporting absolute space and time, claimed that a moving object can have its velocity measured with respect to absolute space. Clarke tried to explain absolute velocity using assumptions, but fundamentally the argument was flawed. Clarke asked how one could distinguish between the universe moving at a constant speed and at rest if absolute space did not exist. If absolute space exists and absolute velocity exists, it should be possible to determine whether the universe is moving at a particular velocity. Without absolute space, the universe could move at some velocity, but there is no way to measure it, which is physically contradictory. Newton's laws must apply to all velocities, but without absolute space, it is impossible to define laws based on velocity.

Leibniz again used PSR and PII to refute absolute velocity. He argued that the concept of absolute velocity contradicts the perfection and rationality of God (PSR). If God set the universe in motion at a specific absolute velocity, but there is no sufficient reason for a particular direction or magnitude, such a decision is unnecessary. Hence, the concept of absolute velocity cannot be philosophically justified. Furthermore, Leibniz emphasized that absolute velocity cannot be experimentally distinguished (PII). Even if the universe moves at a specific absolute velocity, there is no way to detect it. If absolute velocity existed, we should detect the difference experimentally, but no observational difference exists. Therefore, absolute velocity is physically meaningless.

Galileo introduced the principle of relativity, Galilean Relativity, to refute Newton and Clarke's absolute velocity. Galileo conducted experiments on relative velocity on a ship. He observed animals and water droplets inside the cabin, comparing the ship at rest and moving at a constant speed. Experimentally, no distinction could be made, showing that all physical laws apply identically in inertial frames moving at constant speed. From this, Galileo developed relativity (for situations much slower than light speed), demonstrating that relative velocity is physically meaningful.

Based on this, Newtonian physics could be revised. This introduced the concept of Galilean Space-Time. In Galileo's space-time, absolute space is discarded, considering only relative positions and motions, while absolute time is maintained. That is, all observers share the same concept of time. A spacetime diagram can be drawn to describe Newton's laws. In a spacetime diagram, a straight trajectory indicates no external force, a curved trajectory indicates accelerated motion, and the presence of force can be inferred. Using Galilean space-time, only absolute acceleration remains. Velocity may be relative, but acceleration is absolute, which satisfies Newton's laws. Thus, using this method, Newtonian physics can be maintained while removing unnecessary absolute concepts.

History and Philosophy of Modern Physics

However, the absolute notion of space and time from Galileo and Newton did not persist into modern times. Ernst Mach played a key role in rejecting absolute space through a relativistic argument. Mach claimed that the concept of absolute space is unnecessary, and that motion is always defined only in relation to other objects. The convex water surface in rotation does not require absolute space, but is interpreted as water rotating relative to surrounding stars and galaxies (other objects in the universe). This explanation eliminates the need for absolute space, making space relative to stars and galaxies. This influenced Einstein significantly and contributed to the establishment of relativity.

1905 is Einstein's "miracle year." One of the five papers published is the Special Theory of Relativity. Special relativity abolishes the concept of absolute time. Maxwell's equations confirmed that the speed of light in a vacuum is measured identically in any inertial frame, forming the basis for special relativity. Galileo and Newton disagreed about space but believed time to be absolute. If I and my friend George have synchronized clocks and start them simultaneously, 10 seconds later, regardless of our motion, both show 10 seconds. Einstein, however, did not overlook that this long-held belief might be incorrect.

In special relativity, simultaneity can change with the inertial frame. If from my perspective, two boxes 10 m apart explode simultaneously, from George's perspective running fast parallel to the boxes, the events may not be simultaneous. One box may appear to explode before the other, which can be demonstrated using Lorentz transformation.

Also, in special relativity, for George running fast parallel to a ruler, the ruler appears shorter. This is called length contraction; the faster George moves, the shorter the observed length. If absolute space existed, the length could not vary based on the inertial frame. Thus, Einstein saw both space and time as relative, overturning Newton's worldview.

Newton explained physics geometrically. In Principia, he presented laws of motion geometrically, not algebraically. The mathematics of the time was based on Euclidean geometry, and nature and physics occurred in absolute space, so nature was considered geometrically relational. That is, physics was naturally expressed geometrically, not numerically or algebraically.

Newton's E^3 (Euclidean 3D space) system has significantly changed in modern times. Modern space is represented not geometrically but as R^3, the set of real numbers. Algebraic methods, F=ma, and differential equations emerged. Instead of absolute space, space is expressed via coordinates. In modern times, space is algebraic rather than geometric, but this change did not alter the essence of space.

Einstein provided a major turning point regarding absolute space and time through special relativity, changing the paradigm of understanding space and time. However, at that time, Einstein could not explain time and space varying due to gravity, and he was aware of this. In 1907, Einstein conducted a thought experiment showing that effects due to gravity and effects due to accelerated frames of reference cannot be distinguished experimentally. This principle is called the "Equivalence Principle." This thought experiment was revolutionary. However, Einstein could not yet extend it into a theory. At this time, he learned Riemannian geometry from his university friend Grossmann.

Riemannian geometry is an example of non-Euclidean geometry. Euclidean geometry is based on five Euclidean postulates (simple geometry in real life), while non-Euclidean geometry violates one or more of these five. Non-Euclidean geometry originated with the fifth postulate: given a line and a point not on it, there is exactly one line through the point that does not intersect the given line. Scholars tried to prove this postulate indirectly but failed. Gauss created a new geometry without the fifth postulate, called spherical geometry. Gauss first studied non-Euclidean geometry, but Lobachevsky formally published hyperbolic geometry, the first non-Euclidean geometry. Riemann, Gauss's student, compiled the non-Euclidean content into Riemannian geometry. Later mathematicians extended Riemannian geometry and developed tensor analysis.

Einstein began using Riemannian geometry and tensor analysis extensively, and in 1915, he presented the General Theory of Relativity, dealing with spacetime affected by gravity. To date, special and general relativity have not been experimentally falsified and are considered theories that physically explain spacetime. According to these theories, Newton’s absolute space and absolute time do not exist, and physically meaningful quantities are relative space and relative time.

Einstein and 1905: The Hypothesis of an Absolute World

Class 1 23-119 One Choi
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Einstein's university years were greatly influenced by Weber. First, it is necessary to know who Weber was. Wilhelm Eduard Weber was a 19th-century physicist who made significant contributions to electromagnetic theory, presenting Weber's law, which mathematically described the relationship between electricity and magnetism. This law states that the interaction between two charged particles depends on their relative velocity and acceleration. The unit of magnetic flux, Weber, was named after him. Weber also published a doctoral thesis on the theory of light diffraction. While he contributed significantly to electromagnetic laws, he was also interested in practical applications. Consequently, Karl Kappeler, who was the director of the Physics Institute at the Swiss Polytechnic (ETH Zurich), offered Weber a professorship, which he accepted. At that time, ETH Zurich was the university that Einstein enrolled in. Einstein had abandoned the Gymnasium in Munich (a secondary education institution in some European countries) and returned to his family in Milan, which limited his university options. Therefore, he chose ETH Zurich, which accepted students without a Gymnasium diploma. However, Einstein was two years younger than other applicants, so the school initially rejected him. Weber recognized Einstein's genius and arranged for him to attend his lectures as a guest. Einstein was a philosophical thinker who preferred sitting by the lake and daydreaming rather than actively participating in classes. Nevertheless, he was attracted to Weber's sophisticated and precise lectures, and it is evident from Einstein's notes and grades that he attended Weber's lectures diligently and enjoyed them.

Despite this, Einstein was reportedly rude to Weber. Normally, a professor would be addressed as "Professor ___," but Einstein called him "Mr. Weber," which was considered highly disrespectful and unusual. Einstein needed a doctoral advisor at ETH Zurich and requested guidance from Weber, but due to the earlier conflict, Weber refused. Another potential advisor was Jean Pernet, but Einstein only attended one of Pernet's courses, whereas he scored 5–6 out of 6 in Weber's lectures, and only 1 point in Pernet's class. Einstein nearly failed Pernet's class, so it was inevitable that Pernet could not supervise his dissertation. Unable to find an advisor at ETH Zurich, Einstein sought one at the University of Zurich. Through this complicated process, Einstein experienced several periods of doubt about his doctoral thesis.

After several doubts, he ultimately developed the idea of determining molecular size and Avogadro's number through fluid mechanics and submitted it as his doctoral thesis. Einstein's dissertation is also famous for having only one reference. At that time, the existence of atoms and molecules was theoretically accepted, but directly measuring atomic size or experimentally determining Avogadro's number was challenging. Einstein analyzed Brownian motion—the random movement of small particles in a liquid—and provided strong evidence for their actual existence. Furthermore, Jean Perrin experimentally verified Einstein's method with high precision, decisively proving the existence of atoms, for which he was awarded the Nobel Prize in Physics in 1926.

Hermann Minkowski also had significant connections with Einstein. He formalized the spacetime concept in special relativity using a conical coordinate system and unified time and space into a four-dimensional continuum, introducing the concept of a worldline to geometrically interpret special relativity. Minkowski maintained lifelong friendships with mathematicians David Hilbert and Adolf Hurwitz. At Hurwitz's request, Minkowski lectured at ETH Zurich, where one of the students was Einstein. Einstein hardly attended Minkowski's lectures, and Minkowski referred to him as a "born lazybones." However, after reading Einstein's 1905 paper on the electrodynamics of moving bodies, Minkowski was astonished because it closely matched his own contemplations about spacetime. Minkowski further developed this idea and, in 1908, published the paper "Space and Time," which introduced concepts such as spacetime diagrams, worldlines, temporal intervals, and spatial intervals to explain relativity. He is particularly famous for stating, "From now on, space itself and time itself shall fade away like shadows, and only their union shall preserve independent reality." Sadly, Minkowski, who contributed greatly to special relativity, died at the age of 44 in 1909 due to complications from an appendectomy.

Minkowski's concept of the worldline holds significant philosophical meaning, especially regarding the persistence of objects. For example, questions such as "Is the me of yesterday the same as the me of today? And what about the me of tomorrow?" concern persistence. The Ship of Theseus is a famous example of this. This book discusses opposing views on the persistence of objects: perdurantism and endurantism.

According to endurantism, I exist fully at each moment. That is, the "me of today," "me of the past," and "me of tomorrow" each exist independently. It is like the "self" exists frame by frame, as in a movie. This view is more intuitive in daily life, but it cannot guarantee that two selves at different times are the same individual. Even if "the me of ten years ago" is the same as "today's me," the connection is not explicitly ensured.

Those opposing endurantism support perdurantism. According to perdurantism, I exist as an extended entity across time. From birth to death, all moments are connected, forming a continuous existence. In other words, I am a continuous object along the timeline. This concept is well represented by Minkowski's worldline. In a worldline, all my moments are connected in a long line, reflecting Minkowski's support for determinism and his view that past and future coexist simultaneously.

If endurantism describes the self as independent frames in a movie, perdurantism sees the entire film as the self. Additionally, there is stage theory, which combines the advantages of both views. In stage theory, the self exists at each moment, but different selves appear as time progresses. This preserves the intuitiveness of endurantism while incorporating the validity of perdurantism.

Perdurantism is better supported as relativity theory developed. However, this does not completely eliminate endurantism because philosophy and science are not identical. Scientific evidence for perdurantism does not make it the sole philosophical answer. Even if experiments support perdurantism, the experiencing subject—the "I"—still intuitively perceives endurantism, making the picture incomplete.

Question: Quantization of Time
The world is quantized. Does this mean each instant is quantized as well? In other words, is time quantized? If so, how would this affect the validity of perdurantism?

From Bern to Berlin: General Relativity

Class 1 23-119 One Choi
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Einstein's general relativity is a revolutionary theory that explains gravity as the result of spacetime curvature. It renders the previous concepts of absolute space and absolute time meaningless and even challenges the necessity of the ether, which was once thought to mediate gravity. This chapter covers an overview of general relativity and its historical background.

Einstein developed general relativity based on what he called his "happiest thought" in 1907. This idea, commonly referred to as the equivalence principle, originated from his thought experiment that a person falling from a roof would not be able to detect gravity. Furthermore, the equivalence principle states that the effects produced by an accelerating frame of reference are indistinguishable from those produced by gravity. Since an observer cannot differentiate the two situations through any physical experiment, the physical laws must remain the same. To express this idea in precise mathematical language, Einstein adopted 4-dimensional Riemannian geometry, a form of non-Euclidean geometry, and applied the distance function tensor.

First, relativity means that objects or concepts do not exist independently but gain meaning in comparison or relation to others. The idea of relativity traces back to Galileo's ship experiment, and general relativity is a large-scale extension of this experiment's theory. Galileo observed that physical experiments inside and outside a ship yielded the same laws of mechanics. This invariance is also called symmetry.

In 1916, Einstein submitted the paper *The Foundation of the General Theory of Relativity* to the *Annalen der Physik*. The paper can be divided into four main parts. The first part explains why an extension from special relativity was necessary and how natural laws relate to general covariance. Special relativity described the invariance of physical laws only in inertial frames of reference, but inconsistencies arose when observing Maxwell's equations and the Lorentz force inside versus outside the ship. Einstein considered this a failure of Newtonian mechanics and treated Newton's equations as approximate. To resolve this and encompass all general situations, he established general relativity, in which physical laws are identical in all coordinate systems, not just inertial ones. He further argued that general laws of nature must satisfy the condition of general covariance; in other words, covariance was chosen as the mathematical tool to represent the gravitational field. Covariance means that physical laws retain the same form in any coordinate system, which is a central concept of general relativity. Einstein, using the fortunate insight of the equivalence principle, explained gravity and spacetime under general covariance. One could argue that discussing covariance, rather than just the relativity between two coordinate systems, is a more accurate way to frame special and general covariance theories.

The second core topic introduces the tensors and related mathematical tools to describe the gravitational field. Third, he derived the equations of motion for test particles and the field equations of gravity using the variational principle. Fourth, he addressed the extension of general relativity. Applying the theory to fluids or electromagnetism shows that in weak gravity, it reproduces Newton-Poisson theory. Einstein also explained the bending of light (gravitational lensing) and the perihelion precession of Mercury (relativistic effects due to solar orbit). He corrected his earlier calculation of light deflection from 0.83 arcseconds to 1.6 arcseconds.

According to Einstein's general relativity, gravity is like fictitious forces such as centrifugal or Coriolis forces. Just as centrifugal and Coriolis forces arise from coordinate transformations, gravity arises from the curvature of spacetime and is similarly a "fictitious" force. Mathematically, Einstein's gravitational field equations can be written as

(spacetime curvature) = (gravitational constant) × (matter distribution)

This formulation satisfies the principle of general covariance under any coordinate transformation. Using tensors, it becomes

$$A_{\mu\nu} = GT_{\mu\nu}$$

Einstein initially did not know the exact form of A. The Ricci tensor was a candidate, but it failed to reproduce Newton-Poisson equations in the weak-field limit. The final form, known as the Einstein tensor, is a combination of the Ricci tensor, scalar curvature, and metric tensor. Thus, Einstein connected spacetime and gravity, producing a profound insight into both.

The history of this theory is tied to the period after Einstein's 1905 paper on the electrodynamics of moving bodies. Initially, his work on special relativity did not attract much attention until Max Planck praised the young, unknown Einstein, sparking public interest. At that time, Einstein had the confidence that he could answer any question presented to him, despite working full-time at the patent office. He also pursued research outside of his official work. Einstein wrote his habilitation thesis to qualify for a professorship and succeeded at age 29. When a theoretical physics associate professor position opened at the University of Zurich, he applied and was selected. By 1912, he became a full professor at ETH Zurich.

The following year, Einstein and Grossmann collaborated on gravity theory. The resulting equations were invariant only under linear transformations, which did not satisfy Einstein's desire for general covariance. Around this time, Max Planck invited Einstein to Berlin with a special offer: a full professorship at the University of Berlin with a special salary and the option to lecture, along with the directorship of the Wilhelm Physics Institute. Einstein accepted immediately and devoted himself to research. Despite his dedication, he could not initially escape the linear-invariant equations. Only Einstein recognized the flaw in this approach. He eventually abandoned linear invariance and focused on general covariance, publishing the final observational results of his new gravitational theory in late 1915.

In fact, David Hilbert played a significant role in achieving the final form of Einstein's gravitational equations. Hilbert sent Einstein a draft in November, which greatly influenced him. However, Hilbert, already a renowned figure, humbly credited the achievement to the young physicist, Einstein. Therefore, while Einstein systematically established general relativity, it was not solely his effort, and it is arguably fair to refer to the equations as the Hilbert-Einstein gravitational field equations.

Question: Classical Gravitational Lensing
I am curious about explaining gravitational lensing using classical mechanics. From a classical perspective, how can a massless light particle bend?

Schwarzschild: Cosmology

Class 1 23-119 One Choi
2025/03/25

Einstein's general theory of relativity was announced in December 1915, yet the first paper that fully demonstrated it was published the following spring, in March 1916. This four-month gap occurred largely because of one of the protagonists of this section, Karl Schwarzschild. Theoretical physics requires experimental verification to confirm its results, and Schwarzschild played a key role in this verification process. He was the first person to solve and apply Einstein's field equations.

Schwarzschild was a prodigy from a young age. At 16, he calculated the orbits of binary stars and submitted two papers in celestial mechanics. At 23, he earned his doctorate at the University of Munich studying Poincaré's theories. Although primarily an astronomer, he possessed exceptional mathematical and physical computation skills and authored over 120 papers across optics and electromagnetism, contributing significantly to these fields. By age 28, he became a professor at the University of Göttingen, collaborating with Hilbert and Minkowski, and also served as director of the university's astronomical observatory.

Schwarzschild was initially quite skeptical of Einstein's approach. Nevertheless, when Einstein's relativity papers were published, he quickly understood and became the first to solve them. Though not formally a mathematical physicist, he had long been interested in Mercury's perihelion precession—a problem he had observed under the guidance of his doctoral advisor, von Zeipel. After Einstein published general relativity and provided results nearly matching the currently known values of Mercury's precession, Schwarzschild was deeply impressed.

Immediately after Einstein's 1915 papers, Schwarzschild assumed a spherically symmetric, time-independent special case and derived an exact solution using Einstein's theory. Einstein's gravitational field equations are notoriously difficult to solve, even under such simplifying assumptions, because they are nonlinear systems of differential equations. The metric tensor contains ten independent functions, and solving them is only the beginning; further manipulations involving Christoffel symbols and numerous sums must follow. Schwarzschild was the first to solve these notoriously complex field equations in a special case, greatly contributing to Einstein's work. Tragically, Schwarzschild passed away on the very day Einstein published his 1916 paper, never seeing the publication of his own solution.

After Schwarzschild, general relativity continued to develop. Physicists such as Droste, Lense, and Nordström provided explicit solutions. The theory gained prominence in cosmology, especially for studying the dynamics of extremely massive celestial objects. For instance, describing black holes or quasars at galaxy centers requires general relativity, as approximate methods fail under such strong gravity. This led to more detailed discussions of the geometrodynamics underlying general relativity and, eventually, explanations of phenomena such as black hole evaporation and gravitational collapse.

As mentioned earlier, theoretical physics blooms only when verified by observation. Newton's theory initially faced significant opposition because the notion that universal gravity decreases with the square of distance seemed almost mystical. General relativity was similarly non-intuitive. Since strong gravity occurs only around very massive objects, verifying Einstein's theory on Earth was difficult. Verification relied on gravitational lensing. Starlight bends due to spacetime curvature caused by the Sun's gravity. Classical Newtonian mechanics predicted a deflection of 0.8 arcseconds, whereas Einstein predicted approximately double that, 1.6 arcseconds. Verification was delayed because sunlight is too intense—requiring a total solar eclipse—and measurements of starlight without the Sun necessitated waiting an additional six months, among other historical factors.

After World War I, in 1919, Eddington sent two expeditions to measure this effect: one to Sobral and another to Príncipe. The Sobral results were 0.93 arcseconds, and Príncipe measured 1.93 arcseconds. Despite lower precision at Príncipe, their results were adopted, confirming Einstein's theory. In 1979, with modern corrections, both expeditions showed values close to 1.6 arcseconds, but at the time, these early results were contentious and considered hasty.

Besides Schwarzschild, Edwin Hubble and Georges Lemaître also made significant contributions to astrophysics. Their relationship was strained. Hubble's law, in simple terms, describes the expansion of the universe. However, two years before Hubble published his law, Lemaître independently discovered the universe's expansion and even quantitatively determined the rate. This is known as the de Sitter effect. Lemaître calculated the ratio of galaxy recession speed to distance as 625 km/s/Mpc. Despite this, Hubble received most of the credit, and Lemaître's work was initially censored and omitted. Hubble was arrogant, ignoring his assistant Humason, who played a critical role in establishing Hubble's law. Even when Lemaître's contributions were later recognized, Hubble did not cite him. Today, the law is called the "Hubble–Lemaître Law," but chronologically, "Lemaître's Law" or "Lemaître–Hubble Law" would be more accurate.

Another example of distorted history in cosmology occurred in the U.S. in the 1900s. Alpher entered MIT, studying the origin of the universe and cosmology, and during his PhD research met Gamow to study nucleosynthesis. In 1948, he published his thesis, but Gamow removed the name of Alpher's key co-researcher Robert Herman without consent and inserted a non-contributing physicist, Bethe, as a middle author as a pun on "alpha, beta, gamma" in the American Physical Review.

Thus, the history of cosmology has been especially prone to distortion. Many narratives portray a single hero discovering the universe's essence, but this is misleading. In reality, each paper emerges from the combined efforts of numerous brilliant scientists.

Question:
Most physical constants are irrational numbers, expressed as infinite decimals. However, some constants, like Planck's constant or the speed of light, are defined as rational numbers because the SI

system uses them to define units. Why did God create physical constants as complex irrational numbers? Or is there a new unit system or theoretical framework yet to be discovered that could express these constants as “perfect numbers”?

Quantum Recipes

Class 1 23-119 One Choi
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In science, a “recipe” or procedure does not represent a provable law but rather a means to successfully predict phenomena. From a methodological perspective, the recipe is very important. Compared to quantum mechanics, chaos in recipes is minimal in classical mechanics. Much of classical mechanics can be explained intuitively, and even non-intuitive phenomena can be described using existing theories. In quantum mechanics, however, the simple, intuitive approaches often fail.

The first step of the recipe is to assign a wavefunction to the electron. When an electron passes through a slit, the resulting pattern resembles the one produced by a wave passing through the slit. Assigning a wavefunction to an electron may therefore seem natural. However, it is emphasized that this wavefunction is mathematically meaningful but has no direct physical interpretation. The assignment of a wavefunction introduces the complex plane, where vectors rotate to generate phase. These wavefunctions satisfy linear superposition, which enables the principle of wave interference. Max Born gave physical meaning to the wavefunction by proposing that the square of its norm represents the probability density of finding the electron at a given location. Although this interpretation is not rigorously proven, it successfully explains observed phenomena and underpins the Copenhagen interpretation, the mainstream framework today.

The second step of the recipe is to find a law describing how the wavefunction evolves over time. The wavefunction concept remains quite localized; its range of applicability and formalism developed gradually. Louis de Broglie first proposed the concept of matter waves: if light, previously thought to be a wave, exhibits particle-like behavior, could particles also exhibit wave behavior? From this counterintuitive idea and symmetry considerations, he developed matter-wave theory. This concept relates to Bohr’s idea of quantized angular momentum. Bohr proposed that the electron’s angular momentum is quantized, initially a mere hypothesis. Based on matter-wave theory, one can see that if the electron wave forms a standing wave along a circular orbit, angular momentum quantization is satisfied. Erwin Schrödinger formulated the equation governing the time evolution of the electron’s wavefunction. In a potential-free space, the Schrödinger equation resembles classical wave equations for elastic waves, strings, or temperature distributions. Schrödinger’s equation became a fundamental tool for calculating quantum behaviors, such as particle probabilities and energy levels, completing the second step of the recipe.

The final step is to identify the laws that describe physical phenomena. The double-slit experiment, fundamental in quantum mechanics, illustrates this. Thomas Young’s early 19th-century experiment demonstrated that light behaves as a wave. However, the quantum revolution arose when electrons were used. If the electron’s path is observed, it produces two distinct lines as expected classically. If unobserved, it creates an interference pattern like light. The non-intuitive aspect is the dependence of outcomes on observation. Various interpretations exist, with the mainstream view being that the wavefunction collapses to a single path upon measurement, eliminating interference. Calculations rely on the superposition principle.

Next, electron spin is introduced. Stern–Gerlach experiments revealed that electrons possess an additional degree of freedom, later identified as spin. Passing electrons through a magnetic field splits them into two groups: spin-up and spin-down. Spin is highly non-intuitive. First, the electron's tiny radius makes it physically impossible to carry that angular momentum classically. Second, intrinsic angular momentum obeys Heisenberg's uncertainty principle: measuring one axis forces the others into superposition. Spin values and their probability densities can be calculated using matrices and normalized coefficients.

Spin can be entangled, known as entanglement or the singlet state. In Bohm's version of the EPR experiment, two entangled particles passing through separate Stern–Gerlach magnets always show opposite spins: if one is up, the other is down, regardless of distance. Initially in superposition, the wavefunction collapses upon measurement.

Einstein, Podolsky, and Rosen (EPR) found these results counterintuitive. Considering two photons emitted in opposite directions without spin, conservation of angular momentum requires opposite spins. EPR argued that each photon's spin is determined when emitted, implying no "spooky action at a distance." Bell formulated inequalities to test hidden-variable theories. Quantum mechanics alone predicted experimental results accurately and violated Bell inequalities. According to the Copenhagen interpretation, even widely separated particles share a single wavefunction—a mathematical tool—allowing instantaneous collapse. This is interpreted as information update, not faster-than-light interaction. Experiments also confirm that the probability of measuring identical results is proportional to the cosine squared of the angle.

A more advanced experiment is the GHZ experiment (Greenberger–Horne–Zeilinger). Using three entangled electrons in a singlet state, if magnets are aligned along the x-axis, an odd number of spin-up electrons is observed. The possible superpositions include all three up or one up, a total of four states. If electrons carried predetermined spins, contradictions would arise.

Quantum mechanics ultimately reduces to finding eigenvalues and employs operators as mathematical tools. Operators map input wavefunctions to output wavefunctions. Hermitian operators are emphasized: they have real eigenvalues corresponding to physically measurable quantities. For example, the Hamiltonian in Schrödinger's equation is Hermitian and determines both energy measurement and time evolution. Linear operators respect superposition, simplifying calculations. However, operators abstractly conceptualize experimental setups and interactions without providing concrete physical explanations, which is sometimes criticized.

Question:

The wavefunction and Copenhagen interpretation dominate quantum mechanics. However, alternative interpretations—many-worlds, Seoul interpretation, QBism, etc.—exist, predicting the same results. What are the differences between these interpretations and Copenhagen? Among these, which interpretation aligns best with your own view, and why?

Wavefunction and Quantum State

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The very first step of the quantum recipe was to assign a wavefunction to the system. The wavefunction, as described in the chapter on "Quantum Recipe," carries neither more nor less meaning than that of a mathematical function. However, it is natural to ask whether the wavefunction truly represents no meaning at all, since the quantum recipe successfully describes a large number of phenomena.

There are three theories for interpreting the wavefunction. The ψ-ontic theory interprets the wavefunction as actually representing some physical property. It assigns a more complex physical meaning beyond the mathematical function. The ψ-statistical theory explains that the wavefunction does not describe a single system but represents the characteristics when multiple systems are mixed. In particular, Einstein supported this theory. Finally, the ψ-credal theory claims that the wavefunction does not represent any property of the system and only determines the information that we, as observers, acquire. Therefore, the change in the wavefunction is interpreted not as a physical change but as a change in the information acquired by the observer.

In a broader category, wavefunction interpretation can be divided into ontic and epistemic perspectives. The ψ-ontic theory is an interpretation from an ontic perspective, while the ψ-statistical theory and ψ-credal theory interpret the wavefunction from an epistemic perspective.

Each interpretation reflects the properties of electrons very well. Let us first consider the ψ-ontic theory. In the double-slit experiment, when there is no observation, the electron leaves a clear interference pattern, which means it behaves as if passing through both paths simultaneously. This interference is a physical effect that actually exists in space, and it aligns well with the ψ-ontic theory. However, in quantum entanglement experiments such as the EPR experiment, the phenomenon of "spooky action at a distance" appears, which makes it seem as if two particles interact instantaneously regardless of the distance between them. According to Einstein's theory of relativity, an infinite amount of energy would be required to exceed the speed of light, so such interaction is impossible. To address this, ψ-epistemic approaches, more specifically the ψ-credal theory, were developed.

The PBR (Pusey, Barrett, Rudolph) theory concluded in favor of ψ-ontic. The logic of this theory is, in a sense, simple. Suppose an electron can have spin-up along the z-axis or spin-up along the x-axis. But are the two particles physically different? The answer depends on the interpretation of the wavefunction. Ψ-epistemic theories say that two electrons with different spins can share the same physical state S. However, according to the ψ-ontic theory, each wavefunction represents a single physical state, so they must have different physical states. According to the quantum recipe, one can calculate what results occur and determine which interpretation is correct.

In experiments, assume two independent electrons are emitted. Since each electron has two possible spins, there are four independent states in total. When these prepared electrons are measured, there are measurement outcomes that cannot exist for any state. This implies that all preparation states cannot correspond to a single shared physical state S. If ψ-epistemic theory were correct, all states could be grouped into the same S, but experimental results refute this. However, this does not completely reject ψ-statistical or ψ-credal theories. The results only indicate that two electrons with z-axis and x-axis spin must correspond to different physical states, and thus part of the ψ-ontic approach must be correct.

To summarize, understanding the quantum world has greatly advanced through Bell inequalities and the PBR theory. According to Bell's theory, two distant particles cannot be described solely by independent physical states. In other words, locality does not align with the quantum recipe. The PBR theory proves that the wavefunction, a mathematical tool corresponding to each system, must reflect the real physical properties of the system. Both theories, however, are based on the premise of "statistical independence." Both experiments assume that particles are in a state in which the experimenter cannot know which experiment will be performed.

Then, what is a quantum state? A quantum state could be clearly defined as a real physical property represented by the wavefunction Ψ, but we have not yet found out what it is. The author states that it is meaningless to categorize the quantum state philosophically into entities such as substance, property, or relation, because a quantum state could be a new kind of reality unlike anything we previously knew. Therefore, the central questions are: what physical properties correspond to the mathematical characteristics of the wavefunction? Can multiple independent quantum states exist for a system, or is there only a single quantum state? Regarding the last question, quantum entanglement plays an important role. When two systems are entangled, each cannot be described independently by its own wavefunction; only a combined wavefunction for the two systems exists. Applying this logic sequentially, one could conclude that only a single fundamental wavefunction exists for the entire universe. Furthermore, there also exists a **density matrix** to predict properties of subsystems. However, the density matrix fundamentally cannot describe interactions or relationships concerning two entangled particles.

Although quantum states cannot be clearly defined, they are inherently global. One could even view that only a single, gigantic quantum state encompassing the entire universe exists. Nevertheless, no one knows the wavefunction of the entire universe. Yet, scientists have successfully predicted results using the quantum recipe, which leaves many questions regarding quantum states.

Questions:
If particles interact with each other so that the entire universe exists as a single gigantic quantum state, can completely independent systems exist? Philosophically, what does it mean if the universe has multiple quantum states?

Collapse Hypothesis and Local Reality

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In the previous chapter, it was demonstrated through the PBR theorem that the quantum mechanical wavefunction must possess a physical reality, and this was defined as the quantum state. Consequently, the quantum recipe must also reflect this physical reality. The first step of the quantum recipe is to assign a wavefunction to the system, and the second step is to calculate the evolution of the wavefunction using the Schrödinger equation. The Schrödinger equation describes how the wavefunction and its energy change with respect to time and space through a differential equation. The Schrödinger equation represents deterministic evolution. By solving this equation, one can compute the wavefunction at any arbitrary time and location.

However, problems arise in Born's interpretation. The first problem is the sudden introduction of the concept of probability. Up to the Schrödinger equation, everything is determined, but in Born's interpretation, it is interpreted probabilistically. The second problem is that while the wavefunction is a mathematical function spread globally, probability is local. To address this, a new physical interpretation must be devised. The third problem concerns "measurement." Born's interpretation specifies that it applies when measurement occurs, but it does not clarify what should be measured or whether the measured values are accurate. Consequently, Born's interpretation fails to clearly define the probabilistic nature and its conditions of application, and while quantum formulas succeed in predicting phenomena, they do not provide a clear explanation of physical reality.

To address this, we examine the collapse of the wavefunction during measurement in more detail. A characteristic of collapse theories is that they allow non-deterministic and non-linear dynamics. This permits the previously awkward transition from the Schrödinger equation to Born's interpretation. Moreover, this theory is said to be informationally complete, meaning that knowing the given quantum state allows one to know all physical facts about the system. The most representative theory, as always, is the GRW theory, named after three physicists. This theory systematizes the spontaneous collapse of the wavefunction in nature and quantitatively describes when and how collapses occur. Previous theories claimed that collapse occurs through measurement, predicting that a free electron in vacuum would not collapse. In contrast, GRW theory posits that, on average, a spontaneous collapse occurs every 10^{15} seconds (about 100 million years). When a collapse occurs, the wavefunction collapses to the eigenstate of the operator being measured. However, if a position or observable is completely specified, an infinitely steep delta function would be required, implying infinite energy and physical impossibility. GRW theory thus collapses the wavefunction into a Gaussian function, setting a width to prevent infinite slopes while maintaining consistency with Born's interpretation.

This interpretation also holds at macroscopic scales. As mentioned, GRW theory predicts that a particle can spontaneously collapse roughly once every 100 million years. Macroscopic objects like Schrödinger's cat consist of over 10^{27} entangled particles. For many entangled particles, numerous particles collapse nearly instantaneously, making it probabilistically impossible to observe the cat in a superposition of alive and dead states. In standard quantum interpretation, collapse occurs the moment an observer interacts or measurement occurs, whereas GRW theory posits that collapse can naturally occur independently of measurement.

However, issues arise concerning local beables, or local reality. In quantum mechanics, the wavefunction is defined not in three dimensions but in a higher-dimensional configuration space. Yet our measurements and macroscopic objects like cats exist in three dimensions. Therefore, interpreting how the features of the wavefunction manifest in three dimensions is problematic. To address this, John Bell proposed the flash ontology. In GRW theory, spontaneous collapses occur at specific spacetime coordinates, which are interpreted as flashes. While individual particles rarely collapse, macroscopic objects contain many particles, producing continuous flashes. For instance, the human body contains approximately 10^{28} electrons, resulting in over 10^{13} flashes per second. This distribution expresses human form and motion. At microscopic scales, such as individual cells, flash density is very low, so the depiction of reality diminishes. This theory differs from previous interpretations by explaining wavefunction collapse and physical reality without measurement or observer intervention, but it challenges intuition because the microstructure of the world consists only of flashes, which conceptually feels unfamiliar.

Conversely, another GRW-based approach is the matter-density ontology. This interpretation asserts that the squared magnitude of the wavefunction represents the actual density distribution of the particle. For example, if an electron's wavefunction has values 0.25 and 0.75 on the left and right, respectively, it means that 25% of the electron exists on the left and 75% on the right. However, this approach generates the "tail problem." GRW collapse multiplies the wavefunction by a Gaussian to localize it. The Gaussian never truly reaches zero, so the electron is never completely removed from any location. Although initially considered a significant issue, it is now regarded as negligible at macroscopic scales. Furthermore, this approach can be extended to the Continuous Spontaneous Localization (CSL) theory, which has no jumps and can be smoothly expanded. Flash ontology, by contrast, requires jumps and cannot be extended similarly.

However, David Albert rejected introducing matter-density and flash ontologies in GRW theory. He argued that the wavefunction in GRW theory alone suffices to account for the macroscopic world. Albert attempted to represent positions using a causal map. The author demonstrated that this concept is ambiguous and flawed. Albert proposed that projecting particles moving in higher-dimensional space into three dimensions produces shadows of macroscopic objects, but these projections do not constitute actual existence. Explaining macroscopic objects' behavior or structure without local reality is conceptually ambiguous. Thus, Albert concluded that conflating physical reality and mathematically projected shadows leads to logical contradictions.

GRW theory mathematically explains spontaneous collapse by multiplying the wavefunction with a Gaussian function. This allows quantum states to change and collapse to occur without observation. The question is whether this theory can explain experimental phenomena and the behavior of macroscopic objects in the laboratory. The answer is that GRW provides accurate predictions. For instance, in double-slit experiments, the single electron leaving a dot on the screen can be explained through local realism. If GRW collapse occurs at a specific location, a local reality, such as a flash or density, selects a single path, corresponding to experimental data. GRW theory also accurately predicts non-local correlations in entanglement experiments like EPR and violations of Bell inequalities. Of course, GRW is not perfect; some predicted effects have yet to be observed experimentally, but it holds significant value in the philosophy of physics.

Question: In GRW theory, collapse is described by multiplying the wavefunction with a narrow Gaussian. As the width decreases, position uncertainty decreases, leading to increased momentum uncertainty. Can GRW theory account for energy conservation?

Pilot-Wave Theory

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The pilot-wave theory is an interpretation proposed from the early days of quantum mechanics. de Broglie first presented it at the Solvay Conference, and it was later developed by David Bohm. Hence it is called the de Broglie–Bohm theory, or the Bohm interpretation. The pilot-wave theory does not regard the electron as either particle *or* wave in an exclusive sense, but considers that both really exist. In other words, a quantum object is explained as a particle whose motion is guided by a wave (a pilot). In the textbook-standard quantum mechanics such as the Copenhagen interpretation, the wavefunction collapses upon measurement and yields probabilistic outcomes; in the pilot-wave theory the wavefunction does **not** collapse. The particle always exists at a definite location while the wavefunction spreads over space and determines the particle's motion. Another real entity that determines particle motion in this theory is the quantum state (the wavefunction). The wavefunction is nonlocal: when several particles are entangled, the state of one particle can immediately affect the motion of a distant other particle.

To handle multiple particles, the theory employs the concept of configuration space. At any moment, the actual arrangement of particles is represented as a point in configuration space, and this point evolves continuously in time. The wavefunction is a scalar field defined on configuration space that assigns a value to each point; it lives in a much higher-dimensional configuration space (higher than three dimensions) and contains information about the entire particle configuration. The concrete structure depends on whether particles are distinguishable. For N distinguishable particles, a point in configuration space can be represented as a point in \mathbb{R}^{3N}; this is interpreted as listing the x, y, z coordinates of each particle (3N numbers). By contrast, for identical (i.e., indistinguishable) particles, the configuration space is represented as a set of N points in \mathbb{R}^3.

In the pilot-wave theory the wave obeys the Schrödinger equation. This is identical to standard quantum-mechanical dynamics. The difference in pilot-wave theory is that there is an additional guidance equation which specifies how particles move. Given the wavefunction, one can define a vector field on configuration space that gives the velocity for each particle configuration, thereby establishing the rule that determines the dynamics. Concretely, the instantaneous velocity of a particle is proportional to the spatial derivative of the wavefunction's phase. An important point in this theory is that the wavefunction **never** collapses; even when a measurement occurs the wavefunction may branch or become effectively non-overlapping, but it does not probabilistically vanish or converge to a single outcome. Thus the pilot-wave theory is fully deterministic: the guidance equation and the Schrödinger equation, with given initial conditions, determine the entire future. Consequently there is no underlying stochastic process in which events are randomly selected — apparent randomness in the real world is explained as our ignorance of exact initial conditions.

Quantum mechanics fundamentally uses probabilities when making experimental predictions. For example, in a simple spin measurement we predict “up” with 50% probability but do not tell the exact result. Yet pilot-wave theory is deterministic and does not invoke fundamental randomness — how then does it reproduce the statistical quantum predictions? Pilot-wave theory postulates a distribution for initial particle positions. As mentioned, one cannot determine exact initial conditions in an individual experiment, which introduces a statistical hypothesis. The pilot-wave theory assumes that the initial particle positions are distributed according to the wavefunction’s probability density $|\psi|^2$.

How this assumption connects to actual predictions can be illustrated with the double-slit experiment. When electrons are sent one by one toward the slits, pilot-wave theory holds that each electron’s motion is guided by the wavefunction. Depending on various possible initial positions, electrons follow different trajectories after the slits and strike the screen at different points. If initial positions across the beam cross-section are distributed uniformly according to $|\psi|^2$, then the ensemble of many impacts forms a pattern on the screen proportional to $|\psi|^2$. This result exactly matches standard quantum-mechanical probability predictions. So how does a single definite outcome appear at measurement without wavefunction collapse? Measurement causes the wavefunction to branch into components corresponding to different possible results, but the actual particle follows only one branch. Because these branches become entangled with complex external environments, their overlap in configuration space becomes essentially zero, leaving only one effective outcome.

The greatest significance of the pilot-wave theory is that it provides definite outcomes in the quantum world. Particles exist at definite positions like classical particles, and superpositional vagueness is removed. Using configuration space to encode nonlocal interactions, the theory can also account for entanglement between distant particles. The theory offers a concise explanation via deterministic differential equations that is intuitively acceptable and reduces many conceptual confusions. Why then is it not the mainstream textbook interpretation? The author attributes this to sociological reasons: after the Copenhagen interpretation became dominant historically, alternative interpretations were marginalized. However, with renewed interest in realist interpretations, the pilot-wave theory is being revisited.

Pilot-wave theory still has room to develop. It is judged successful in the nonrelativistic domain. However, extension to the relativistic domain remains problematic. In the nonrelativistic view, time is absolute and the theory is formulated in an absolute temporal frame, so the temporal order of two spacelike-separated events is fixed. But according to relativity, the temporal ordering of distant timelike-interval events may change depending on the observer. Pilot-wave theory involves determination according to some specific order, so an account is required. Several proposals exist: for example, introducing a new structure of spacetime, or modifying basic concepts to reconcile nonlocality with a relativistic framework.

The pilot-wave theory is considered one of the most successful attempts to understand quantum phenomena in classical-intuitive terms. With clear ontology and deterministic laws, it provides a coherent account of measurement, duality, and nonlocality. While not currently mainstream, it remains a steadily researched alternative interpretation that offers conceptual clarity and physical compatibility.

Question

How is the guidance equation in pilot-wave theory derived?

Many-Worlds Interpretation

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Another interpretation that emerged to solve the measurement problem in quantum mechanics is Hugh Everett's many-worlds interpretation. This interpretation resolves the measurement problem while preserving the linear evolution of the wavefunction, and by assuming the completeness of the wavefunction, it interprets that when a single initial quantum state evolves into a superposition of multiple outcomes, each of the superposed states actually exists. For example, in the case of a measuring device, when measuring an electron in a superposition of up-spin and down-spin, the wavefunction of the system evolves into a superposition of the case where the measured spin points up and the case where it points down. According to Everett, both cases exist in reality, and one says that the world has branched into two.

Everett's concept of branching was innovative, but the criterion was extremely free. As long as the wavefunction of some system is expressed in the form $a|\varphi> + b|\chi>$, Everett claimed that $|\varphi>$ and $|\chi>$ each constitute an independent branch and therefore a real world. As a result, in practice, infinitely many branches of worlds always coexist. However, this raises the problem of what criterion should be used to divide the world. According to Everett's principle, since an infinite number of superpositions can be represented depending on the choice of basis, the criterion for which superposition defines the real world becomes ambiguous. This is called the problem of the preferred basis. Proponents of the many-worlds interpretation argued that the phenomenon of decoherence through interaction with the environment naturally selects a specific basis. Since the mathematical structure of this interpretation is symmetric for all bases, the definition of worlds divided into branches is not completely rigorous, leaving interpretive leeway. Another ontological problem is how the many-worlds interpretation defines local physical reality. The wavefunction is a state defined in 3N-dimensional configuration space, and it does not correspond one-to-one with localized particles or fields in physical space. However, the many-worlds interpretation cannot discuss local ontology beyond the wavefunction. The author also criticized this as an incomplete theory, pointing out that the issue of spacetime locality remains unresolved. Everett, for the time being, omitted this part and continued his discussion.

The measurement problem refers to the contradiction that, before measurement, the system's wavefunction exists in a superposition state, but upon actual measurement, only one result is observed. The many-worlds interpretation attempted to solve the measurement problem by completely eliminating the assumption of wavefunction collapse. Instead, it claimed that a superposed state entangled with the measuring device arises in the system, and when each component ceases to interfere with each other through decoherence with the environment, each exists as a separate world. Thus, no probabilistic intervention exists, and the measurement problem is solved by the claim that the universe branches every time a measurement is made.

However, at this cost, the many-worlds interpretation had to accept the concept of a vast multiverse. Since the universe splits whenever a measurement occurs, an enormous number of worlds come into existence each time. According to Everett's generous criterion, infinitely many branching worlds always exist, making the ontology both richer and stranger. Since these multiple worlds cannot interact with each other, they are extremely difficult to empirically verify. In the end, the concept of actual existence was sacrificed, which became a major point of controversy among philosophers and physicists.

Following the measurement problem is the issue of probability. Born's rule states that the probability density of a measurement outcome is proportional to $|\psi|^2$, but in the many-worlds interpretation, since all outcomes actually occur, this creates a problem. The author highlights this issue. In the GRW theory, probability is inherent in the law itself, so Born's rule is well established. In de Broglie–Bohm's pilot-wave theory, probabilistic concepts can be introduced by assuming ignorance of the initial positions and conditions of particles. However, in the many-worlds interpretation, the wavefunction fully describes the state and is essentially deterministic, so such probabilistic interpretation is impossible. In the original paper, Everett attempted to interpret relative frequencies, but expressed its meaninglessness. As a result, the interpretation faces criticism for failing to explain the uncertainty of future outcomes from the perspective of individual worlds.

To address this issue, proponents of the many-worlds interpretation explored various approaches. One prominent approach is the decision-theoretic approach. The idea is that even though all outcomes of a single experiment physically occur, an agent who must make a choice before branching will behave as if following traditional probabilistic interpretation. Since a rational agent would make decisions in a way that ultimately aligns with Born's rule regardless of choice, Born's rule is restored through behavior. Once one specifies how a rational agent ought to act, Born's rule acquires meaning. However, this approach still provoked controversy, and the author along with many critics pointed out the remaining issues. Simply put, this approach stipulates how agents ought to behave but fails to explain why the results emerge as they do. Since one must accept these special assumptions, if the assumptions are unconvincing, the approach becomes meaningless. Thus, the question of whether this approach truly restores the meaning of Born's rule remains unresolved.

Through comparison with other interpretations, one can understand the characteristics of the many-worlds interpretation. First, the many-worlds interpretation is among the most daring and radical among interpretations of quantum mechanics. By adhering to the wavefunction and linear evolution—that is, explaining everything with the minimum—it arrives at the reality of countless worlds, which is evaluated as an enormous ontological cost. Nevertheless, it has impressed many theorists as a theory that follows Occam's razor by avoiding superfluous additions. Also, while other interpretations modify physical laws or introduce hidden elements to preserve the intuition that only one reality exists, the many-worlds interpretation leaves physical laws untouched and instead modifies the concept of reality.

The many-worlds interpretation has the following limitations and assessments. First, the problem of probability interpretation remains an unresolved challenge. The internal explanation within the many-worlds interpretation for why Born's rule must apply has not been established convincingly. Some proponents argue that introducing probability concepts into the many-worlds interpretation is a wrong question from the start, but if so, the risk arises that the numerical predictions of quantum mechanics become meaningless. Second, there is strong resistance and skepticism regarding the acceptance of the existence of infinite multiverses that cannot be observed or interacted with. In science, the existence of reality is generally judged by whether it can be observed, but in the many-worlds interpretation, observation itself is causally impossible. Furthermore, the infinite multiverse is criticized for imposing a very high metaphysical cost. Finally, the definition of worlds and the criterion of branching are ambiguous. While Everett claimed that decoherence through the environment provides an effective criterion for branching, strictly speaking, the concept of worlds does not exist in the theory itself. What state should be considered a single world remains the interpreter's choice, which is criticized as seriously undermining scientific clarity.

Because of these limitations, Everett's idea was at one time a theory that did not receive much attention. Some distinguished researchers, however, have taken the many-worlds interpretation seriously or used it as a useful conceptual tool. For example, quantum computing's parallel computation is sometimes metaphorically explained from the viewpoint of parallel worlds, and in cosmology, the initial condition problem has been discussed in terms of multiple worlds. However, most physicists still maintain a conservative stance and adhere to the attitude of "Shut up and calculate." For them, the many-worlds interpretation is interesting but remains a hypothesis that cannot yet be experimentally verified and has not proven decisive advantages over traditional interpretations. The author also emphasizes how conceptually bold the many-worlds interpretation is, and highlights that, accordingly, there remain many philosophical challenges to be solved. In the end, the many-worlds interpretation represents one extreme among interpretations of quantum mechanics and remains, for now, not a complete answer but an interpretation that must continue to be refined and tested.

Question

How is the universe in which my consciousness exists determined? Can the many-worlds interpretation justify this selectivity?

2025-1 History and Philosophy of Physics – Midterm Paper

Class 1 23-119 One Choi

2025.06.21

Appendix – Midterm Exam Answer

Question: What does the principle of symmetry mean in physics? Also, when constructing a physical theory, why is symmetry necessary? Provide a brief example.

Symmetry in physics is the very essence of nature. Symmetry means invariance under some transformation. In fact, symmetry serves as a more fundamental standard than any specific law in physics. When physicists propose a new theory, if it violates symmetry, they question the validity of the theory itself and re-examine it from the ground up. For example, in Maxwell's equations, Galilean transformations fail to preserve their form. Einstein doubted the validity of Galilean transformations, long believed to be true for centuries. Through the theory of special relativity, he modified Galilean transformations and redefined spacetime symmetry. Furthermore, the asymmetry arising when gravity was included in special relativity was addressed through general relativity, thereby reinforcing the symmetric nature of nature. If nature were fundamentally asymmetric and irregular, one could raise the philosophical question of why God created the universe in such a way. However, according to Leibniz's Principle of Sufficient Reason, such an explanation lacks philosophical persuasiveness. God would have no reason to privilege a particular part of nature.

Nature follows order. Stars have orbital periods, food chains form cycles, and the total energy of a system is always conserved. Because nature is symmetric, terms like "period," "cycle," and "conservation" have meaning. Countless future secrets of nature must also be framed within symmetry. Moreover, symmetry is central even at the frontiers of modern particle physics. For example, supersymmetry (SUSY), which assumes every fundamental particle has a symmetric partner, represents an expanded attempt to understand the universe's fundamental structure through symmetry. Such new theories are likewise built on the firm idea of symmetry. If a new law were to break nature's symmetry, we would have to dismantle all of physics built so far and reconstruct it from the foundation.

2025-1 History and Philosophy of Physics – Final Paper

Class 1 23-119 One Choi
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Introduction: The Theories of Space in the Past

Reflection on space began in ancient Greece. In ancient Greece, it was crucial to define space because citizens directly participated in democratic politics in a designated space called the Agora. Many scholars, including Aristotle, believed that the Earth was the center of the universe. Since one feels nothing when staying still, this line of thought seemed natural. Later in the modern era, Galileo Galilei's experiments and the principle of relativity seemed to support the relational perspective, which understands space as a relation among objects. However, Isaac Newton strongly argued for absolute space, which exists independently of matter. He attempted to prove the existence of absolute space through the rotating bucket experiment and a thought experiment involving two connected spheres. For a time, the concept of absolute space enjoyed considerable support in the scientific community. But soon, objections were raised. Leibniz argued that space and motion cannot be viewed as absolute entities, invoking the Principle of Sufficient Reason and the Principle of the Identity of Indiscernibles. In the 19th century, physicist Ernst Mach also opposed Newton's view, countering that the basis for perceiving rotational motion is not abstract absolute space but relative relations with the mass distributed throughout the universe. Mach's ideas greatly inspired Einstein and contributed to the development of the theory of relativity, fundamentally shifting the paradigm of physics. Ultimately, through Leibniz's and Mach's philosophical objections, Einstein's theoretical developments, and subsequent experimental verification, Newton's substantialist concept of absolute space gradually lost credibility, and the relational view of space gained dominant support in modern physics. Within this historical context, a natural question arises: Can Newton's substantialist concept of space ever regain validity? This final paper will examine the possibility of reviving substantialist space theory from several perspectives and argue that its recovery is ultimately impossible.

Possibility of Restoring an Absolute Origin

The first step in establishing a coordinate system is setting an origin. Only after fixing the origin can one define basis vectors and represent coordinates. To establish an absolute spatial coordinate system, an absolute origin is inevitably required. One must first consider whether a privileged point exists in the vast universe. If a point in the universe is not special, there is no reason to set it as the origin. The Big Bang singularity may appear to be the best candidate for an absolute origin. No point in the universe has been as unique as the origin of the universe itself. However, the concept of the Big Bang singularity is a misconception when applied to the present universe. The observed expansion of the universe is homogeneous from the perspective of any observer; it has no center. The balloon model is often used to explain cosmic expansion: if dots are drawn on the surface of a balloon and the balloon is inflated, all dots move apart, but no dot serves as the center. Similarly, since the universe has expanded uniformly in all directions since the Big Bang, there exists no absolute origin anywhere in the present three-dimensional universe. While the singularity may exist when theoretically tracing back to the universe's origin, it cannot be specified as a particular point in today's space. Therefore, it is impossible to assume an absolute origin as a privileged reference, and thus an absolute spatial coordinate system cannot be established.

Possibility of Restoring Absolute Velocity

Absolute velocity is a vacuous concept both philosophically and experimentally. It lacks meaning in both domains. If a fixed background medium pervaded the entire universe, such as ether or the cosmic microwave background (CMB), then every object would have a unique velocity vector relative to it. In that case, Galilean transformations would no longer be fully symmetric, and one could physically distinguish whether an object is at rest or, say, moving eastward at 30 km/s.

There have been multiple attempts to prove the existence of absolute velocity. The most famous is the Michelson–Morley experiment in the late 19th century. Assuming the above hypothesis, the Earth's motion relative to the ether should cause slight variations in the speed of light. However, the experiment showed that the speed of light is constant in all directions, and the Earth's absolute motion relative to ether could not be detected. Based on this failure, Einstein established the theory of special relativity on the principle of invariance of the speed of light, demonstrating that physical laws can be explained without relying on ether. According to special relativity, all inertial frames are physically equivalent, and the concepts of absolute rest or absolute motion are no longer necessary.

Philosophically, dividing two things that cannot be distinguished through observation or experience is meaningless. Borrowing Leibniz's principles, there is no justification for introducing absolute motion if it produces no observable effects. If no measurable difference results, then an object at rest and one moving at constant velocity are indistinguishable physically and experientially, and thus must be regarded as the same state philosophically. Therefore, discussing absolute velocity—indistinguishable and lacking reality—is a vacuous philosophical pursuit.

Possibility of Restoring Absolute Space

Finally, let us consider whether the concept of absolute space itself can be revived. Newton conceived absolute space as an infinite, immutable container existing independently of matter. This concept gained some credibility through Newton's bucket experiment but, as discussed earlier, was seriously undermined by Leibniz's and Mach's philosophical critiques and Einstein's relativity theory. Is there any reason within modern science to restore the concept of absolute space?

At first glance, the CMB appears to provide a universal frame of reference. Observations show that our galaxy moves at hundreds of km/s relative to the CMB, producing anisotropy where the CMB temperature is slightly higher in one direction and lower in the opposite. This seems to suggest that defining velocity relative to the CMB allows for absolute motion, as if Newton's absolute space had re-emerged in modern cosmology. However, upon closer inspection, the CMB frame does not correspond to absolute space in Newton's sense. This is because the frame is defined by the distribution of matter and energy in the universe, not as an inherent property of space itself. Without the CMB, such a frame would not exist, and it would change if the matter distribution were not uniform. Absolute space, by contrast, was assumed to exist independently of matter. The CMB frame, however, is merely a relational frame created by radiation and matter distributed across the universe. Furthermore, according to relativity, physical laws (e.g., the speed of light in vacuum) are the same in all inertial frames, so our motion relative to the CMB does not alter those laws. Thus, the CMB standard does not resurrect absolute space but, on the contrary, illustrates Mach's insight that the meaning of space and motion arises only in relation to the universe's contents.

Conclusion and Summary

We have examined the possibility of restoring absolute origin, absolute velocity, and absolute space. An absolute origin cannot exist due to the nature of cosmic expansion. The concept of absolute velocity lost its physical meaning through the failure of ether-detection experiments and the paradigm shift brought by relativity. The CMB, while providing a cosmological reference, does not reinstate the substantialist concept of space. In sum, the absolute space of substantialist theory cannot be restored in light of modern scientific theories and observations. Space continues to be defined only through relations among matter and events, and the notion of absolute space independent of matter has lost meaning entirely. Therefore, substantialist space theory has no possibility of recovery, and the relational view of space remains the more valid and effective framework.