

AETHERSHIP DESIGN

Einstein-aether theory

In [physics](#) the **Einstein-aether theory**, also called **aetheory**, is the name coined in 2004 for a modification of [general relativity](#) that has a [preferred reference frame](#) and hence violates [Lorentz invariance](#). These [generally covariant](#) theories describes a [spacetime](#) endowed with both a [metric](#) and a unit timelike [vector field](#) named the *aether*. The *aether* in this theory is "a Lorentz-violating vector field"^[1] unrelated to older [luminiferous aether](#) theories; the "Einstein" in the theory's name comes from its use of Einstein's general relativity equation.^[2]

Relation to other theories of gravity

An Einstein-aether theory is an alternative theory of gravity that adds a vector field to the theory of general relativity. There are also scalar field modifications, including [Brans–Dicke theory](#), all included with [Horndeski's theory](#). Going the other direction, there are theories that add tensor fields, under the name [Bimetric gravity](#) or both scalar and vector fields can be added, as in [Tensor–vector–scalar gravity](#).^{[3]:30}

History

The name "Einstein-aether theory" was coined in 2004 by T. Jacobson and D. Mattingly.^[4] This type of theory originated in the 1970s with the work of C.M.Will and K. Nordtvedt Jr. on gravitationally coupled vector field theories.^{[3]:42}

In the 1980's Maurizio Gasperini added a [scalar field](#), which intuitively corresponded to a universal notion of [time](#), to the metric of [general relativity](#).^[5] Such a theory will have a preferred [reference frame](#), that in which the universal time is the actual time.

In 2000, Ted Jacobson and David Mattingly developed a model that allows the consequences of preferred frames to be studied.^[6] Their theory contains less information than that of Gasperini, instead of a scalar field giving a universal time it contains only a unit [vector field](#) which gives the direction of time. Thus observers who follow the aether at different points will not necessarily age at the same rate in the Jacobson–Mattingly theory. In 2008 Ted Jacobson presented a status report on Einstein-aether theory.^[7]

Breaking Lorentz symmetry

The existence of a preferred, dynamical time vector breaks the [Lorentz symmetry](#) of the theory, more precisely it breaks the invariance under [boosts](#). This symmetry breaking may lead to a [Higgs mechanism](#) for the graviton which would alter long distance

physics, perhaps yielding an explanation for recent [supernova](#) data which would otherwise be explained by a [cosmological constant](#). The effect of breaking Lorentz invariance on [quantum field theory](#) has a long history leading back at least to the work of Markus Fierz and [Wolfgang Pauli](#) in 1939. Recently it has regained popularity with, for example, the paper *Effective Field Theory for Massive Gravitons and Gravity in Theory Space* by [Nima Arkani-Hamed](#), [Howard Georgi](#) and Matthew Schwartz.^[8] Einstein-aether theories provide a concrete example of a theory with broken Lorentz invariance and so have proven to be a natural setting for such investigations.

Action

The action of the Einstein-aether theory is generally taken to consist of the sum of the [Einstein–Hilbert action](#) with a [Lagrange multiplier](#) λ that ensures that the time vector is a unit vector and also with all of the covariant terms involving the time vector u but having at most two derivatives.

In particular it is assumed that the [action](#) may be written as the [integral](#) of a local [Lagrangian density](#)

where G_N is [Newton's constant](#) and g is a [metric](#) with [Minkowski signature](#). The Lagrangian density is

Here R is the [Ricci scalar](#), ∇_μ is the [covariant derivative](#) and the tensor K is defined by

Here the c_i are dimensionless adjustable parameters of the theory.

Solutions

[\[edit\]](#)

Stars

[\[edit\]](#)

Several spherically symmetric solutions to ae-theory have been found. Most recently Christopher Eling and [Ted Jacobson](#) have found solutions resembling [stars](#)^[9] and solutions resembling [black holes](#).^[10]

In particular, they demonstrated that there are no spherically symmetric solutions in which stars are constructed entirely from the aether. Solutions without additional matter always have either [naked singularities](#) or else two

asymptotic regions of spacetime, resembling a [wormhole](#) but with no [horizon](#). They have argued that static stars must have *static aether* solutions, which means that the aether points in the direction of a timelike [killing vector](#).

Black holes and potential problems

However this is difficult to reconcile with static black holes, as at the [event horizon](#) there are no timelike Killing vectors available and so the black hole solutions cannot have static aethers. Thus when a star collapses to form a black hole, somehow the aether must eventually become static even very far away from the collapse.

In addition the [stress tensor](#) does not obviously satisfy the [Raychaudhuri equation](#), one needs to make recourse to the equations of motion. This is in contrast with theories with no aether, where this property is independent of the equations of motion.

Experimental constraints

In a 2005 paper,^[11] [Nima Arkani-Hamed](#), Hsin-Chia Cheng, Markus Luty and [Jesse Thaler](#) have examined experimental consequences of the breaking of boost symmetries inherent in aether theories. They have found that the resulting [Goldstone boson](#) leads to, among other things, a new kind of [Cherenkov radiation](#).

In addition they have argued that spin sources will interact via a new inverse square law force with a very unusual angular dependence. They suggest that the discovery of such a force would be very strong evidence for an aether theory, although not necessarily that of Jacobson, *et al*.

Aether theories

From Wikipedia, the free encyclopedia

In the history of [physics](#), **aether theories** (or **ether theories**) proposed the existence of a medium, a space-filling substance or field as a [transmission medium](#) for the propagation of electromagnetic or gravitational forces. Since the development of [special relativity](#), theories using a substantial aether fell out of use in [modern physics](#), and are now replaced by more abstract models.

This [early modern](#) aether has little in common with the [aether](#) of classical elements from which the name was borrowed. The assorted theories embody the various conceptions of this [medium](#) and [substance](#).

Historical models

Luminiferous aether

Main articles: [Luminiferous aether](#) and [History of special relativity](#)

[Isaac Newton](#) suggests the existence of an aether in the Third Book of [Opticks](#) (1st ed. 1704; 2nd ed. 1718): "Doth not this aethereal medium in passing out of water, glass, crystal, and other compact and dense bodies in empty spaces, grow denser and denser by degrees, and by that means refract the rays of light not in a point, but by bending them gradually in curve lines? ...Is not this medium much rarer within the dense bodies of the Sun, stars, planets and comets, than in the empty celestial space between them? And in passing from them to great distances, doth it not grow denser and denser perpetually, and thereby cause the gravity of those great bodies towards one another, and of their parts towards the bodies; every body endeavouring to go from the denser parts of the medium towards the rarer?"^[1]

In the 19th century, [luminiferous aether](#) (or ether), meaning light-bearing aether, was a theorized medium for the propagation of light. [James Clerk Maxwell](#) developed a model to explain electric and magnetic phenomena using the aether, a model that led to what are now called [Maxwell's equations](#) and the understanding that light is an electromagnetic wave.^[2] Later, a series of increasingly careful experiments were carried out in the late 1800s, including the [Michelson–Morley experiment](#), to try to detect the motion of Earth through the aether, but no drag was detected. A range of proposed [aether-dragging theories](#) could explain the null result but these were more complex, and tended to use arbitrary-looking coefficients and physical assumptions. [Joseph Larmor](#) discussed the aether in terms of a moving magnetic field caused by the acceleration of electrons.

[Hendrik Lorentz](#) and [George Francis FitzGerald](#) offered, within the framework of [Lorentz ether theory](#), an explanation of how the Michelson–Morley experiment could have failed to detect motion through the aether. However, the initial Lorentz theory predicted that motion through the aether would create a [birefringence](#) effect, which [Rayleigh](#) and [Brace](#) tested and failed to find ([Experiments of Rayleigh and Brace](#)). All of those results required the full application of the [Lorentz transformation](#) by Lorentz and [Joseph Larmor](#) in 1904.^{[3][4][5][6]} Summarizing the results of Michelson, Rayleigh and others, [Hermann Weyl](#) would later write that the aether had "betaken itself to the land of the shades in a final effort to elude the inquisitive search of the physicist".^[7] In addition to possessing more conceptual clarity, [Albert Einstein](#)'s 1905 [special theory of relativity](#) could explain all of the experimental results without referring to an aether at all. This eventually led most physicists to conclude that the earlier notion of a luminiferous aether was not a useful concept.

Mechanical gravitational aether

Main article: [Mechanical explanations of gravitation](#)

From the 16th until the late 19th century, gravitational effects had also been modeled using an aether. In a note at the end of his work "A Dynamical Theory of the Electromagnetic Field", Maxwell discussed a model for gravity based on a medium similar to the one he used for the electromagnetic field. He concluded that the medium would have "an enormous intrinsic energy" and would necessarily have to be diminished in areas of mass. He could not "understand in what way a medium can possess such properties" so he did not pursue it further.^[8] The most well-known

formulation is [Le Sage's theory of gravitation](#), although variations on the idea were entertained by [Isaac Newton](#), [Bernhard Riemann](#), and [Lord Kelvin](#). For example, Kelvin published a note on Le Sage's model in 1873, in which he found Le Sage's proposal [thermodynamically](#) flawed and suggested a possible way to salvage it using the then popular [vortex theory of the atom](#). Kelvin later concluded

This kinetic theory of matter is a dream, and can be nothing else, until it can explain chemical affinity, electricity, magnetism, gravitation, and the inertia of masses (that is, crowds) of vortices. Le Sage's theory might give an explanation of gravity and of its relation to inertia of masses, on the vortex theory, were it not for the essential aeolotropy of crystals, and the seemingly perfect isotropy of gravity. No finger post pointing towards a way that can possibly lead to a surmounting of this difficulty, or a turning of its flank, has been discovered, or imagined as discoverable.^[9]

None of those concepts are considered to be viable by the scientific community today.

Non-standard interpretations in modern physics

General relativity

Main article: [Einstein's views on the aether](#)

Albert Einstein sometimes used the word *aether* for the gravitational field within [general relativity](#), but the only similarity of this relativistic aether concept with the [classical aether](#) models lies in the presence of physical properties in space, which can be identified through [geodesics](#). As historians such as [John Stachel](#) argue, Einstein's views on the "new aether" are not in conflict with his abandonment of the aether in 1905. As Einstein himself pointed out, no "substance" and no state of motion can be attributed to that new aether.^[10] Einstein's use of the word "aether" found little support in the scientific community, and played no role in the continuing development of modern physics.^{[11][12]}

Quantum vacuum

Main article: [Quantum vacuum state](#)

[Quantum mechanics](#) can be used to describe [spacetime](#) as being non-empty at extremely small scales, fluctuating and generating [particle pairs](#) that appear and disappear incredibly quickly. It has been suggested by some such as [Paul Dirac](#)^[13] that this [quantum vacuum](#) may be the equivalent in modern physics of a particulate aether. However, Dirac's aether hypothesis was motivated by his dissatisfaction with [quantum electrodynamics](#), and it never gained support from the mainstream scientific community.^[14]

Physicist [Robert B. Laughlin](#) has suggested that the quantum vacuum could be viewed as a "relativistic ether".^[15] [Paul Davies](#) writes that while the quantum vacuum resembles in some ways the old concept of the aether, the two differ in a key respect: the quantum vacuum "has no privileged reference frame, no state of rest relative to which a material body could be said to move."^[16]

Pilot waves

Main articles: [Pilot wave](#) and [De Broglie–Bohm theory](#)

[Louis de Broglie](#) stated, "Any particle, ever isolated, has to be imagined as in continuous "energetic contact" with a hidden medium."^{[17][18]} However, as de Broglie pointed out, this medium "could not serve as a universal reference medium, as this would be contrary to relativity theory."^[17]

Demystifying the Aether: From Early Light Wave Theories to Einstein's Relativity Revolution

November 17, 2023

The luminiferous aether has an intriguing history in the evolution of physics. This hypothetical medium was once thought to permeate all space and enable light propagation. But what exactly was the aether? Why did physicists posit its existence? And how did experiments and Einstein's relativity ultimately dismiss it? Let's explore the curious case of the vanished aether.

Setting the Stage: Early Theories of Light as Waves

Long before Einstein, Isaac Newton viewed light as a stream of particles. But in the early 1800s, landmark experiments by Thomas Young and Augustin-Jean Fresnel showed light could exhibit wave properties. This sparked a paradigm shift.

Suddenly, physicists realized light needed a medium to ripple through, just as sound waves travel through air. This medium was christened the "luminiferous aether." It was conceived as an invisible fluid filling all space and permeating all matter.

This aether supposedly allowed light waves to propagate the same way sound propagates through water or air. It was also thought to provide an absolute frame of reference for motion through space.

Pinning Down the Elusive Aether

Throughout the mid-1800s, physicists struggled to quantify the aether's properties. Some theories depicted it as a fluid similar to water while others suggested it behaved more like a solid.

Experiments set out to measure effects like "aether drag" in an attempt to characterize this ephemeral medium.

Many luminaries bought into the aether hypothesis, including James Clerk Maxwell. His famous equations describing electromagnetism were premised on the aether's existence. But repeated efforts to validate this theoretical entity kept coming up empty-handed.

The Michelson-Morley Experiment: A Null Result for the Ages

In 1887, Albert Michelson and Edward Morley conducted a seminal test to pin down the aether. Their ingenious apparatus, now called the Michelson interferometer, was designed to detect subtle changes in the speed of light caused by Earth's movement through the stationary aether.

But try as they might, the duo found no evidence of "aether wind." The speed of light stubbornly remained constant regardless of Earth's motion. This monumental null result baffled physicists and kicked off a crisis in the classical worldview.

| Michelson-Morley Experimental Results |
| - | - |
| Attempt | Measured Change in c |
| Along Earth's Orbital Path | 0 km/s |
| Perpendicular to Orbital Path | 0 km/s |

Clearly, something was amiss with the reigning theories about light and aether. But what exactly? More precise repetitions of the Michelson-Morley experiment continued to yield null results, deepening the confusion. Only Einstein's radical insights could ultimately make sense of it.

Einstein to the Rescue: Relativity Dethrones the Aether

In 1905, Einstein's special theory of relativity resolved the issues raised by Michelson, Morley, and other failed aether experiments. He discarded the notion of absolute space and time in favor of relative motion.

Most importantly, Einstein postulated a constant speed of light in a vacuum, unchanging regardless of an observer's motion. This new conception of light rendered the luminiferous aether obsolete. Einstein boldly declared it did not exist at all!

According to Einstein's relativity, light can propagate as electromagnetic waves without requiring a medium. Empty space itself allows the transmission of light. The previously hypothesized aether was surplus to requirements.

Einstein's counterintuitive insights took some time to gain traction in the physics community. But relativity ultimately prevailed,

consigning the aether theory to the dustbin of scientific history. Or so it seemed...

The Aether Strikes Back? Modern Resurrections

Despite relativity eliminating the classical luminiferous aether, various revamped versions have appeared in speculative physics. Quantum mechanics in particular has motivated renewed interest.

One example is the Einstein-Aether theory proposed in the 1990s. This model tries to reconcile quantum theory with relativity by introducing a "dynamic aether." However, it remains controversial and most physicists reject a true return to aether theories of old.

Some other speculative connections have arisen between the aether concept and perplexing phenomena like dark matter and dark energy. But robust empirical evidence for these conjectures remains elusive.

While echoes of the luminiferous aether linger, Einstein's insights still provide the best working model of light, relativity, and the nature of space-time. The original motivation for positing a light-conducting aether is simply no longer present in modern physics.

The Winding Journey to Relativity: What We Learned

The rise and fall of the aether showcases how science progresses in fits and starts down winding paths. The luminiferous aether went from intriguing hypothesis to supposed fact to fictional relic. This serpentine journey teaches us much about the scientific endeavor.

First, it shows that “common sense” theories can prove misguided. Before Einstein, an invisible light-conducting medium seemed logical. But nature does not bend to our notions of common sense. Scientific truth emerges from experiment and mathematics, not intuition. As the physicist Richard Feynman noted, “It does not make any difference how smart you are, who made the guess, or what his name is – if it disagrees with experiment it is wrong.”

Second, the aether saga reveals that negative results hold great value. Michelson and Morley “failed” to find the sought-after medium. But this null result set physics down the path that led to Einstein’s breakthroughs. As the old saying goes, “Today’s failed experiment is tomorrow’s new theory.”

Finally, the luminiferous aether’s demise teaches us that even firmly entrenched ideas can rapidly lose favor if they do not fit the evidence. In science, no notion is sacred if the data contradict it. As Isaac Asimov said, “The most exciting phrase to hear in science, the one that heralds new discoveries, is not ‘Eureka!’ but ‘That’s funny...’” The nonexistence of the ether certainly seemed funny before relativity elucidated light’s true nature.

The Aether: Gone but Not Forgotten

What can we conclude about the concept of an intangible medium for light propagation? The original luminiferous aether theory has certainly been superseded thanks to Einstein. But it still looms large in the history of physics and reminds us that yesterday’s “facts” may be tomorrow’s fiction.

Some ideas resembling the classical aether do creep up now and then at physics’ frontiers. However, the specific notion of a stationary space-filling medium underpinning light waves remains

consigned to the past. Like phlogiston and caloric, the luminiferous aether turned out to be a fictional placeholder rather than a real entity.

But this discontinued model of light propagation still advanced understanding by revealing flaws in old theories. As the scientist Humphry Davy observed, "Nothing tends so much to the advancement of knowledge as the application of a new instrument." The aether theory served as a prod pushing physics toward relativity, much as Ptolemaic epicycles led towards Copernican heliocentrism.

So while the aether faded away, the knowledge gained lives on in relativity and quantum electrodynamics. This persistent enrichment of insight makes deprecated concepts like the aether worth revisiting. As Isaac Newton remarked, "If I have seen further it is by standing on the shoulders of giants." By climbing atop the luminiferous aether, physics saw farther still.

Aether (classical element) According to ancient and [medieval science](#), **aether** (/ˈiːθər/, alternative spellings include *æther*, *aither*, and *ether*), also known as the **fifth element** or **quintessence**, is the material that fills the region of the [universe](#) beyond the [terrestrial sphere](#).^[1] The concept of aether was used in several theories to explain several natural phenomena, such as the propagation of light and gravity. In the late 19th century, physicists postulated that aether permeated space, providing a medium through which light could travel in a [vacuum](#), but evidence for the presence of such a medium was not found in the [Michelson–Morley experiment](#), and this result has been interpreted to mean that no [luminiferous aether](#) exists.^[2]

Mythological origins

Main article: [Aether \(mythology\)](#)

See also: [Empyrean](#)

The word αἰθήρ (*aithér*) in [Homeric Greek](#) means "pure, fresh air" or "clear sky".^[3] In [Greek mythology](#), it was thought to be the pure essence that the gods breathed, filling the space where they lived, analogous to the [air](#) breathed by mortals.^[4] It is also personified as a deity, [Aether](#), the son of [Erebus](#) and [Nyx](#) in traditional Greek mythology.^[5] Aether is related to αἶθω "to incinerate",^[6] and intransitive "to burn, to shine" (related is the name *Aithiopes* ([Ethiopians](#); see [Aethiopia](#)), meaning "people with a burnt (black) visage").^{[7][8]}

Fifth element



Medieval concept of the cosmos. The innermost spheres are the terrestrial spheres, while the outer are made of aether and contain the celestial bodies.

In [Plato's *Timaeus*](#) (58d) speaking about air, Plato mentions that "there is the most translucent kind which is called by the name of aether (αἰθήρ)"^[9] but otherwise he adopted the classical system of four elements. [Aristotle](#), who had been Plato's student at the [Academy](#), agreed on this point with his former mentor, emphasizing additionally that fire has sometimes been mistaken for aether. However, in his Book [On the Heavens](#) he introduced a new "first"

element to the system of the [classical elements](#) of [Ionian philosophy](#). He noted that the four terrestrial classical elements were subject to change and naturally moved linearly. The first element however, located in the celestial regions and heavenly bodies, moved circularly and had none of the qualities the terrestrial classical elements had. It was neither hot nor cold, neither wet nor dry. With this addition the system of elements was extended to five and later commentators started referring to the new first one as the fifth and also called it *aether*, a word that Aristotle had used in *On the Heavens* and the *Meteorology*.^[10]

Aether differed from the four terrestrial elements; it was incapable of motion of quality or motion of quantity. Aether was only capable of local motion. Aether naturally moved in circles, and had no contrary, or unnatural, motion. Aristotle also stated that [celestial spheres](#) made of aether held the stars and planets. The idea of aethereal spheres moving with natural circular motion led to Aristotle's explanation of the observed orbits of stars and planets in perfectly circular motion.^{[11][12]}

Medieval scholastic philosophers granted *aether* changes of density, in which the bodies of the planets were considered to be more dense than the medium which filled the rest of the universe.^[12] [Robert Fludd](#) stated that the aether was "subtler than light". Fludd cites the 3rd-century view of [Plotinus](#), concerning the aether as penetrative and non-material.^[13]

Quintessence



A stylized *Q* is sometimes used as a symbol for quintessence. ^[citation needed]

The symbol for aether in the works of [Torbern Bergman](#) (ca. 1775)

Quintessence (*Q*) is the [Latinate](#) name of the fifth element used by medieval alchemists for a medium similar or identical to that thought to make up the heavenly bodies. It was noted that there was very little presence of quintessence within the terrestrial sphere. Due to the low presence of quintessence, earth could be affected by what takes place within the heavenly bodies.^[14] This theory was developed in the 14th century text *The testament of Lullius*, attributed to [Ramon Llull](#).^[citation needed] The use of quintessence became popular within medieval alchemy. Quintessence stemmed from the medieval elemental system, which consisted of the four classical elements, and aether, or quintessence, in addition to two chemical elements representing metals: [sulphur](#), "the stone which burns", which characterized the principle of combustibility, and [mercury](#), which contained the idealized principle of metallic properties.

This elemental system spread rapidly throughout all of Europe and became popular with alchemists, especially in medicinal alchemy. Medicinal alchemy then sought to isolate quintessence and incorporate it within medicine and elixirs.^[14] Due to quintessence's pure and heavenly quality, it was thought that through consumption one may rid oneself of any impurities or illnesses. In *The book of Quintessence*, a 15th-century English translation of a continental text, quintessence was used as a medicine for many of man's illnesses. A process given for the creation of quintessence is [distillation](#) of alcohol seven times.^[15] Over the years, the term quintessence has become synonymous with [elixirs](#), medicinal [alchemy](#), and the [philosopher's stone](#) itself.^[16]

Legacy

Main article: [Aether theories](#)

With the [18th century physics developments](#), physical models known as "aether theories" made use of a similar concept for the explanation of the propagation of electromagnetic and gravitational forces. As early as the 1670s, Newton used the idea of aether to help match observations to strict mechanical rules of his physics.^{[17][a]} The early modern aether had little in common with the aether of classical elements from which the name was borrowed. These aether theories are considered to be scientifically obsolete, as the development of [special relativity](#) showed that [Maxwell's equations](#) do

JACOBI BERNOULLI
DISSERTATIO
DE
GRAVITATE
ÆTHERIS.



AMSTELÆDAMI
Apud HENR. WETSTENIUM
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not require the aether for the transmission of these forces. Einstein noted that his own model which replaced these theories could itself be thought of as an aether, as it implied that the empty space between objects had its own physical properties.^[19]

Despite the early modern aether models being superseded by general relativity, occasionally some physicists have attempted to reintroduce the concept of aether in an attempt to address perceived deficiencies in current physical models.^[20] One proposed model of [dark energy](#) has been named "[quintessence](#)" by its proponents, in honor of the classical element.^[21] This idea relates to the hypothetical form of dark energy postulated as an explanation of observations of an accelerating universe. It has also been called a [fifth](#)

[fundamental force](#).

Aether and light

Main article: [Luminiferous aether](#)

The motion of light was a long-standing investigation in physics for hundreds of years before the 20th century. The use of aether to describe this motion was popular during the 17th and 18th centuries, including a theory proposed by [Johann II Bernoulli](#), who was recognized in 1736 with the prize of the French Academy. In his theory, all space is permeated by aether containing "excessively small whirlpools". These whirlpools allow for aether to have a certain elasticity, transmitting vibrations from the corpuscular packets of light as they travel through.^[22]

This theory of [luminiferous aether](#) would influence the [wave theory](#) of light proposed by [Christiaan Huygens](#), in which light traveled in the form of [longitudinal waves](#) via an "omnipresent, perfectly elastic medium having zero density, called aether". At the time, it was thought that in order for light to travel through a vacuum, there must have been a medium filling the void through which it could propagate, as sound through air or ripples in a pool. Later, when it was proved that the nature of light wave is [transverse](#) instead of longitudinal, Huygens' theory was replaced by subsequent theories proposed by [Maxwell](#), [Einstein](#) and [de Broglie](#), which rejected the existence and necessity of aether to explain the various optical phenomena. These theories were supported by the results of the [Michelson–Morley experiment](#) in which evidence for the motion of aether was conclusively absent.^[23] The results of the experiment influenced many physicists of the time and contributed to the eventual development of Einstein's [theory of special relativity](#).^[24]

Aether and gravitation

[Jakob Bernoulli](#), *De gravitate aetheris*, 1683

In 1682, [Jakob Bernoulli](#) formulated the theory that the hardness of the bodies depended on the pressure of the aether.^[25] Aether has been used in various gravitational theories as a medium to help explain gravitation and what causes it.



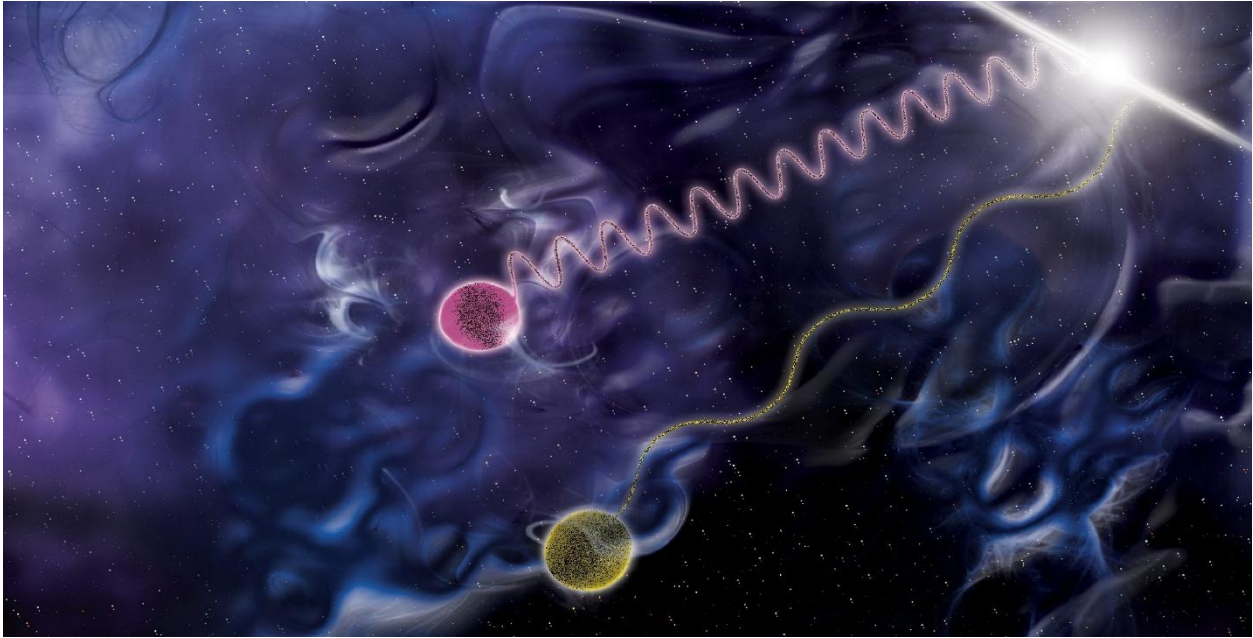
Sir [Isaac Newton](#)

A few years later, aether was used in one of Sir [Isaac Newton](#)'s first published theories of gravitation, [Philosophiæ Naturalis Principia Mathematica](#) (the *Principia*, 1687). He based the whole description of planetary motions on a theoretical law of dynamic interactions. He renounced standing attempts at accounting for this particular form of interaction between distant bodies by introducing a mechanism of propagation through an intervening medium.^[26] He calls this intervening medium aether. In his aether model, Newton describes aether as a medium that "flows" continually downward toward the Earth's surface and is partially absorbed and partially diffused. This "circulation" of aether is what he associated the force of gravity with to help explain the action of gravity in a non-mechanical fashion.^[26] This theory described different aether densities, creating an aether density gradient. His theory also proposed that aether is rarified within objects and dense outside them. As particles of denser aether interact with the rare aether they are attracted back to the dense aether much like cooling vapors of water are attracted back to each other to form water.^[27] In the *Principia* he attempts to explain the elasticity and movement of aether by relating aether to his static model of fluids. This elastic interaction is what caused the pull of gravity to take place, according to this early theory, allowing gravity to be explained in terms of action through direct contact instead of action at a distance, which Newton considered "an absurdity".^[28] Newton also explained this changing rarity and density of aether in his letter to [Robert Boyle](#) in 1679. He illustrated aether and its field around objects in this letter as well and used this as a way to inform Robert Boyle about his theory.^[27] Although Newton eventually changed his theory of gravitation to one involving force and the laws of motion, his starting point for the modern understanding and explanation of gravity came from his original aether model on gravitation.^[29]^[self-published source?]

MAY 11, 2023

Is there any evidence that the “aether” exists?

Contrary to common experience, not everything needs a medium to travel through. Overcoming that assumption removes the need for an aether.



The longer a photon's wavelength is, the lower in energy it is. But all photons, regardless of wavelength/energy, move at the same speed: the speed of light. This is, surprisingly, irrespective of the motion of the observer relative to light; the speed of light is the same for all observers.

KEY TAKEAWAYS

- It was assumed that light waves, just like sound waves, pressure waves, and water waves, required a medium to travel through.
- Even though that medium was never directly detected, people assumed its properties and even gave it a name: the luminiferous aether.
- But all experiments failed to reveal this suspected medium, and special and general relativity at last did away with the need for it entirely. Can we point to any evidence at all in favor of the aether's existence?

All throughout the Universe, different types of signals propagate. Some of them, like sound waves, require a medium to travel through. Others, like light or gravitational waves, are perfectly content to traverse the vacuum of space, seemingly defying the need for a medium altogether. Irrespective of how they do it, all of these signals can be detected from the effects they have on all the matter and energy that they interact with: both along their journey through space all the way up until their eventual arrival at their final destination.

But is it truly possible for waves to travel through the vacuum of space itself, without any need for a “medium” to propagate through at all? For some of us, this is a very counterintuitive notion, as the notion of things existing within and moving through some form of empty nothingness just doesn’t make any sense. But plenty of things in physics don’t make intuitive sense, as it isn’t up to humans to tell nature what does and doesn’t make sense. Instead, all we can do is ask the Universe questions about itself through experiment, observation, and measurement, and follow nature’s answers to the best conclusions we can draw. Although there’s no way to disprove the aether’s (or anything else that’s unobservable) existence, we can certainly look at the evidence and allow it to take us wherever it will.

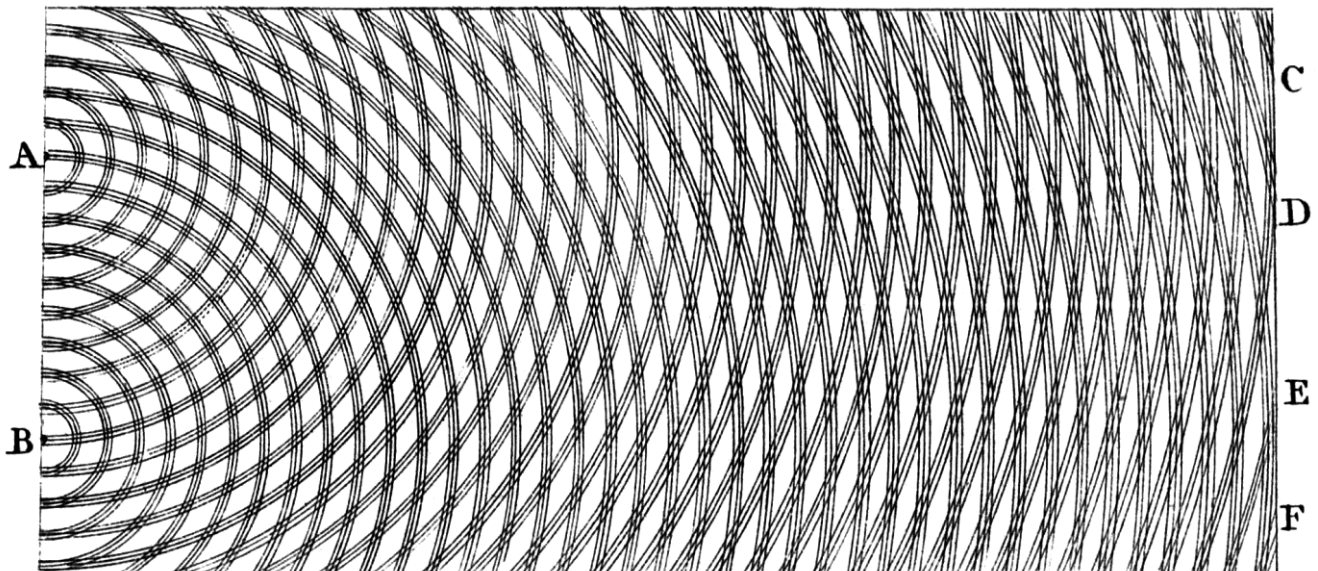


When a disturbance is created in a pond, such as by dropping a stone into an otherwise still body of water, it will generate ripples that propagate circularly outward. Because the waves are confined to the surface of the water, their amplitude will only decrease as $\sim 1/r$, as the waves spread out in a circle, confined to a two-dimensional surface.

Back in the earliest days of science — before Newton, going back hundreds or even thousands of years — we only had large-scale, macroscopic phenomena to investigate. The waves we observed came in many different varieties, including:

- the ripples that wind caused in clothes on a clothesline or on a ship's sails,
- water waves on the sea, ocean, or lake,
- the waves that propagated through the ground during an earthquake,
- the waves that emerged in a tight string that was plucked, struck, or oscillated,
- or even sound waves, whose effects could be felt differently in air, water, or through solid land.

In the case of all of these waves, matter is involved. That matter provides a medium for these waves to travel through, and as the medium either compresses-and-rarifies in the direction of propagation (a longitudinal wave) or

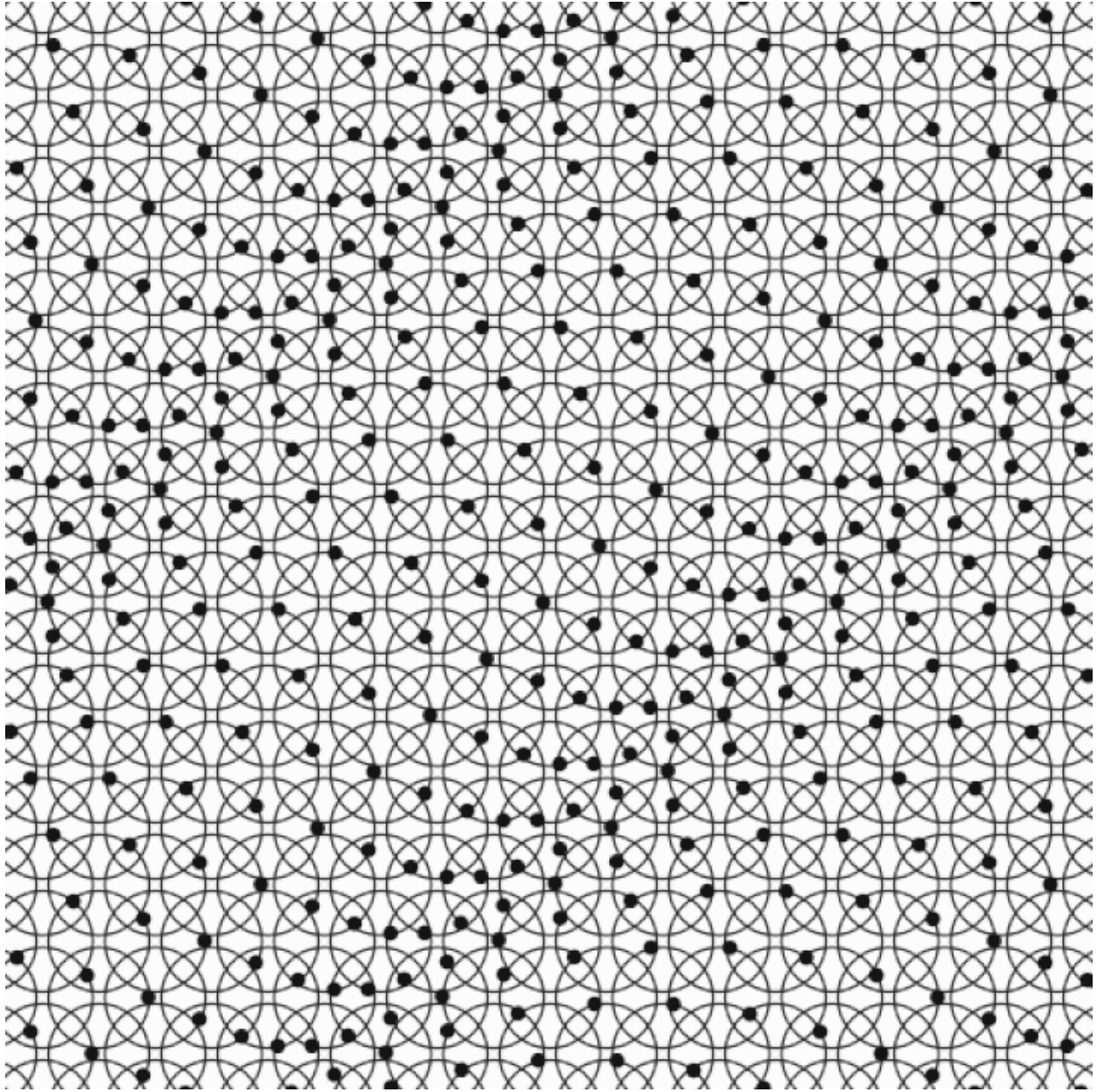


oscillates perpendicular to the direction of propagation (a transverse wave), the signal is transported from one location to another.

This diagram, dating back to Thomas Young's work in the early 1800s, is one of the oldest pictures that demonstrate both constructive and destructive interference as arising from wave sources originating at two points: A and B. This is a physically identical setup to a double slit experiment, even though it applies just as well to water waves propagated through a tank. The locations marked C, D, E, and F correspond to 100% destructive interference.

As we began to investigate waves more carefully, a third type began to emerge. In addition to longitudinal and transverse waves, a type of wave where each of the particles involved underwent motion in a circular path — a surface wave — was discovered. The rippling characteristics of water, which were previously thought to be either longitudinal or transverse waves exclusively, were shown to also contain this surface wave component.

All three of these types of waves are examples of mechanical waves, which is where some type of energy is transported from one location to another through a material, matter-based medium. A wave that travels through a spring, a slinky, water, the Earth, a string, or even the air, all require an impetus for creating some initial displacement from equilibrium, and then the wave carries that energy through a medium toward its destination.

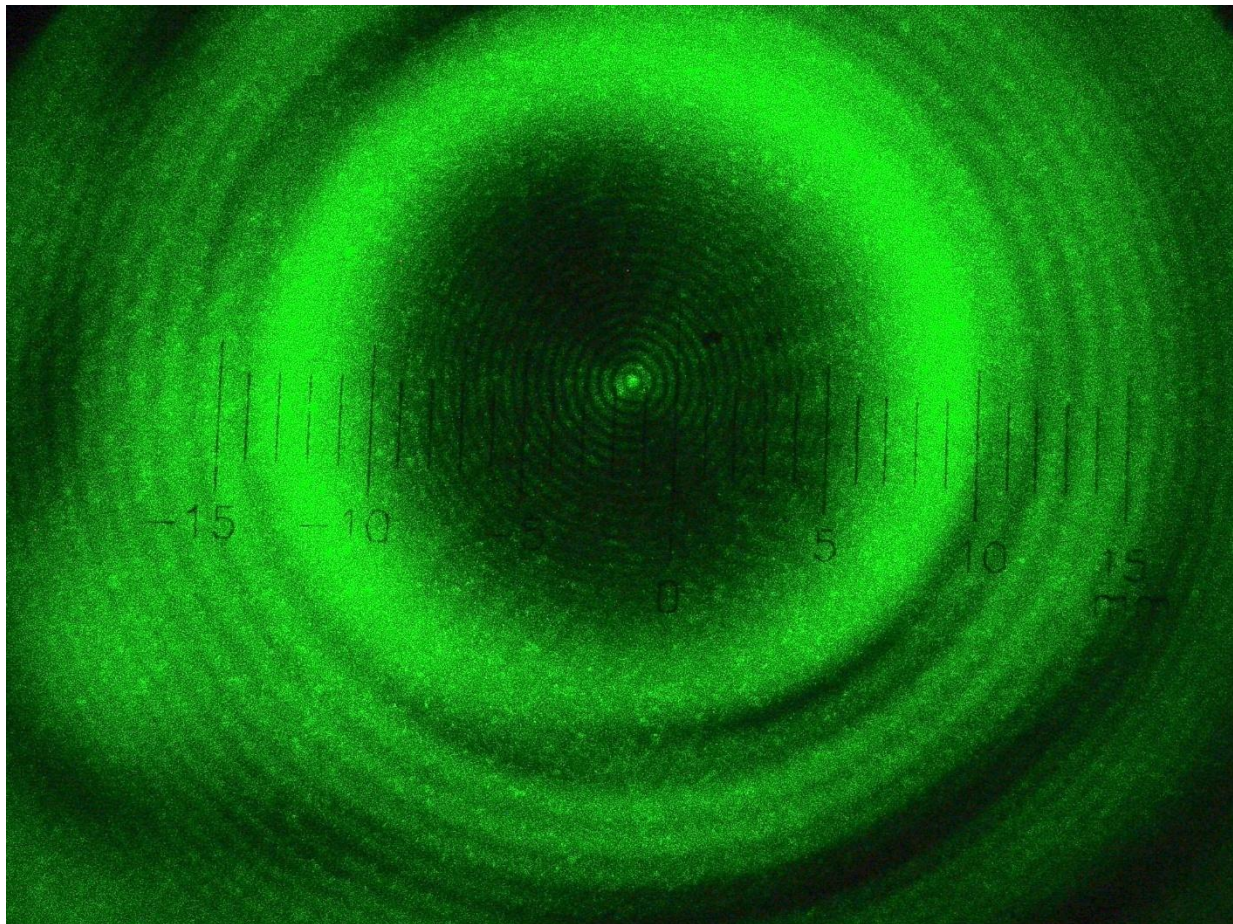


A series of particles moving along circular paths can appear to create a macroscopic illusion of waves. Similarly, individual water molecules that move in a particular pattern can produce macroscopic water waves, individual photons make the phenomenon we perceive as light waves, and the gravitational waves we see are likely made out of individual quantum particles that compose them: gravitons.

It makes sense, then, that as we discovered new types of waves, we'd assume they had similar properties to the classes of waves we already knew about. Even before Newton, the aether was the name given to the void of space, where

the planets and other celestial objects resided. Tycho Brahe's famous 1588 work, *De Mundi Aetherei Recentioribus Phaenomenis*, literally translates as "On Recent Phenomena in the Aethereal World."

The aether, it was assumed, was the medium inherent to space that all objects, from comets to planets to starlight itself, traveled through. Whether light was a wave or a corpuscle, though, was a point of contention for many centuries. Newton claimed it was a corpuscle, while Christiaan Huygens, his contemporary, claimed it was a wave. The issue wasn't decided until the 19th century, [where experiments with light unambiguously revealed its wave-like nature](#). (With modern quantum physics, we now know it behaves like a particle also, but its wave-like nature cannot be denied.)

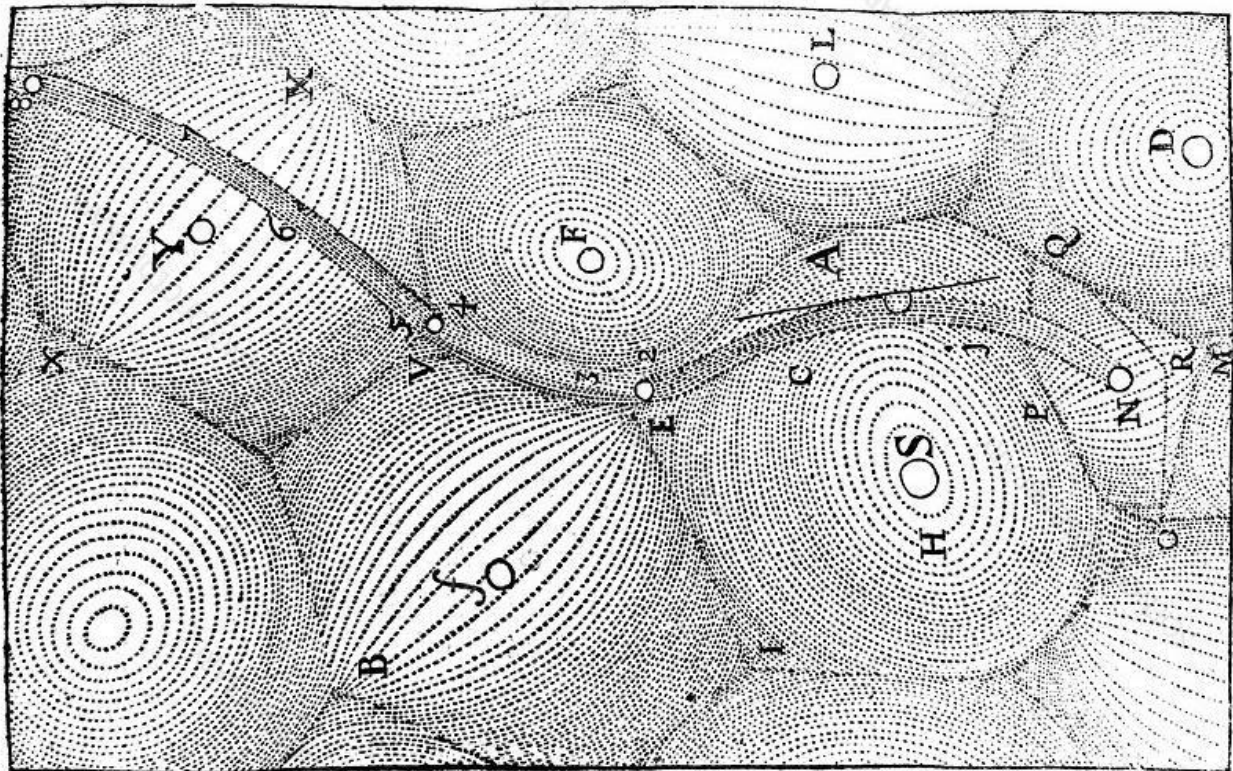


The results of an experiment, showcased using laser light around a spherical object, with the actual optical data. Note the extraordinary validation of Fresnel's theory's prediction: that a bright, central spot would appear in the shadow cast by the sphere, verifying the absurd prediction of the wave theory

of light. Logic, alone, would not have gotten us here; it was only through François Arago's willingness to perform the critical experiment that we learned the underlying scientific truth.

This was further borne out as we began to understand the nature of electricity and magnetism. Experiments that accelerated charged particles not only showed that they were affected by magnetic fields, but that when you bent a charged particle with a magnetic field, it radiated light. Theoretical developments showed that light itself was an electromagnetic wave that propagated at a finite, large, but calculable velocity, today known as c , the speed of light in a vacuum.

If light was an electromagnetic wave, and all waves required a medium to travel through, and — as all the heavenly bodies traveled through the medium of space — then surely that medium itself, the aether, was the medium that light traveled through. The biggest question remaining, then, was to determine what properties the aether itself possessed.



In Descartes' vision of gravity, there was an aether permeating space, and only the displacement of matter through it could explain gravitation. This,

unfortunately, did not lead to an accurate formulation of gravity that matched with observations.

One of the most important points about what the aether *couldn't* be was figured out by Maxwell himself, who was the first to derive the electromagnetic nature of light waves. In an 1874 letter to Lewis Campbell, he wrote:

It may also be worth knowing that the aether cannot be molecular. If it were, it would be a gas, and a pint of it would have the same properties as regards heat, etc., as a pint of air, except that it would not be so heavy.

In other words, whatever the aether was — or more accurately, whatever it was that electromagnetic waves propagated through — it could not have many of the traditional properties that other, matter-based media possessed. It could not be composed of individual particles. It could not contain heat. It could not be a conduit for the transfer of energy through it. In fact, just about the only thing left that the aether was allowed to do was serve as a background medium for things that were known to travel but didn't otherwise seem to require a medium, like light, to actually travel through.

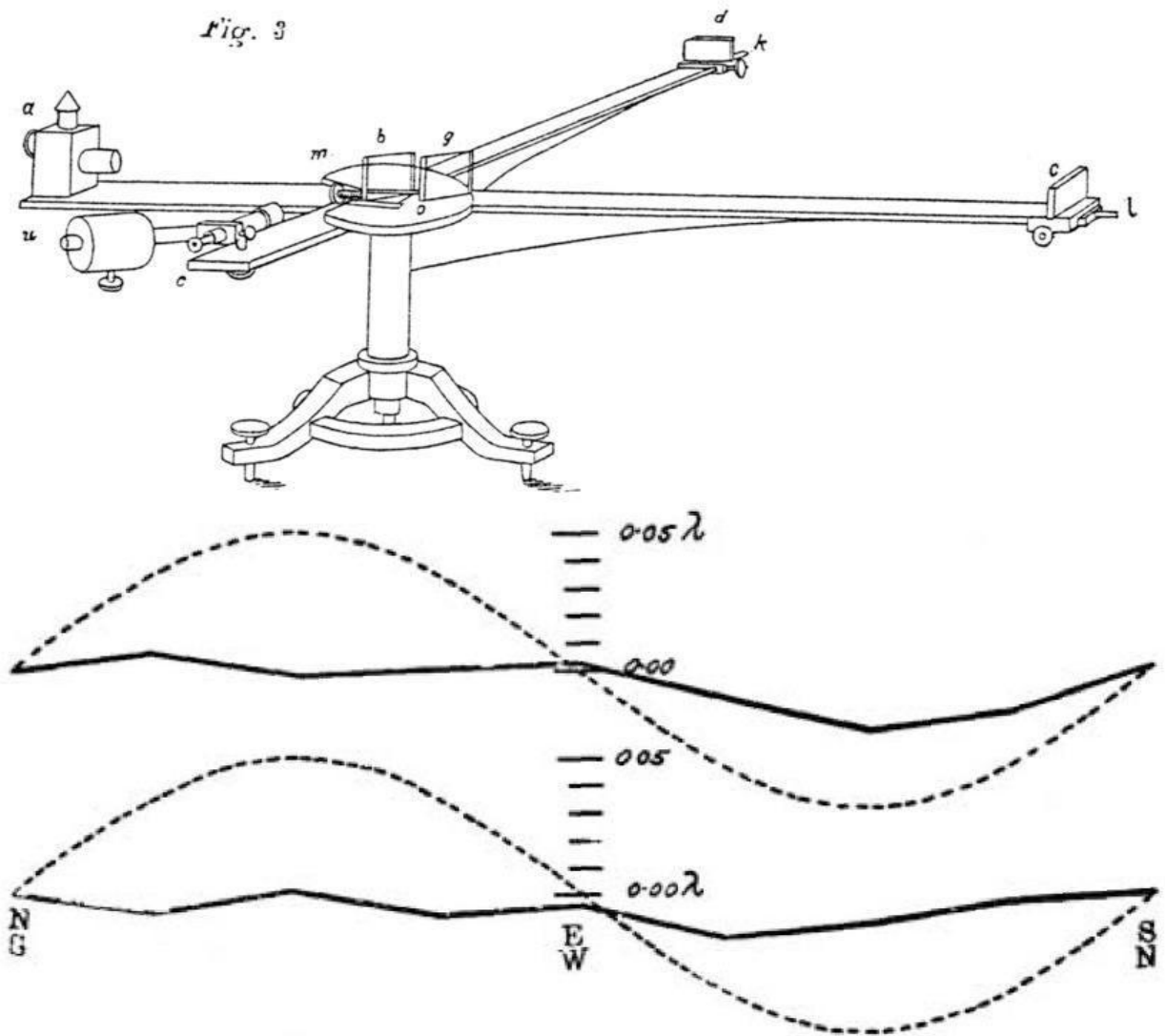


If you split light into two perpendicular components and bring them back together, they will produce an interference pattern. If there's a medium that light is traveling through, the interference pattern should depend on how your apparatus is oriented relative to that motion. If the speed of light is a constant

to all observers, however (a contradiction of Newton's predictions), then light will arrive from even mutually perpendicular directions at the eventual detector simultaneously.

All of this led to the most important experiment for detecting the aether: the Michelson-Morley experiment. If aether really were a medium for light to travel through, then the Earth should be passing through the aether as it rotated on its axis and revolved around the Sun. Even though we only revolve at a speed of around 30 km/s, that's a substantial fraction (about 0.01%) of the speed of light.

With a sensitive enough interferometer, if light were a wave traveling through this medium, we should detect a shift in light's interference pattern dependent on the angle the interferometer made with our direction of motion. Michelson alone tried to measure this effect in 1881, but his results were inconclusive. 6 years later, with Morley, they reached sensitivities that were just 1/40th the magnitude of the expected signal. Their experiment, however, yielded a null result; there was no evidence for the aether at all.



The Michelson interferometer (top) showed a negligible shift in light patterns (bottom, solid) as compared with what was expected if Galilean relativity were true (bottom, dotted). The speed of light was the same no matter which direction the interferometer was oriented, including with, perpendicular to, or against the Earth's motion through space.

Aether enthusiasts contorted themselves in knots attempting to explain this null result.

- Perhaps the aether [was being dragged by objects traveling through space](#), such as the Earth, and that's why a null result was obtained.

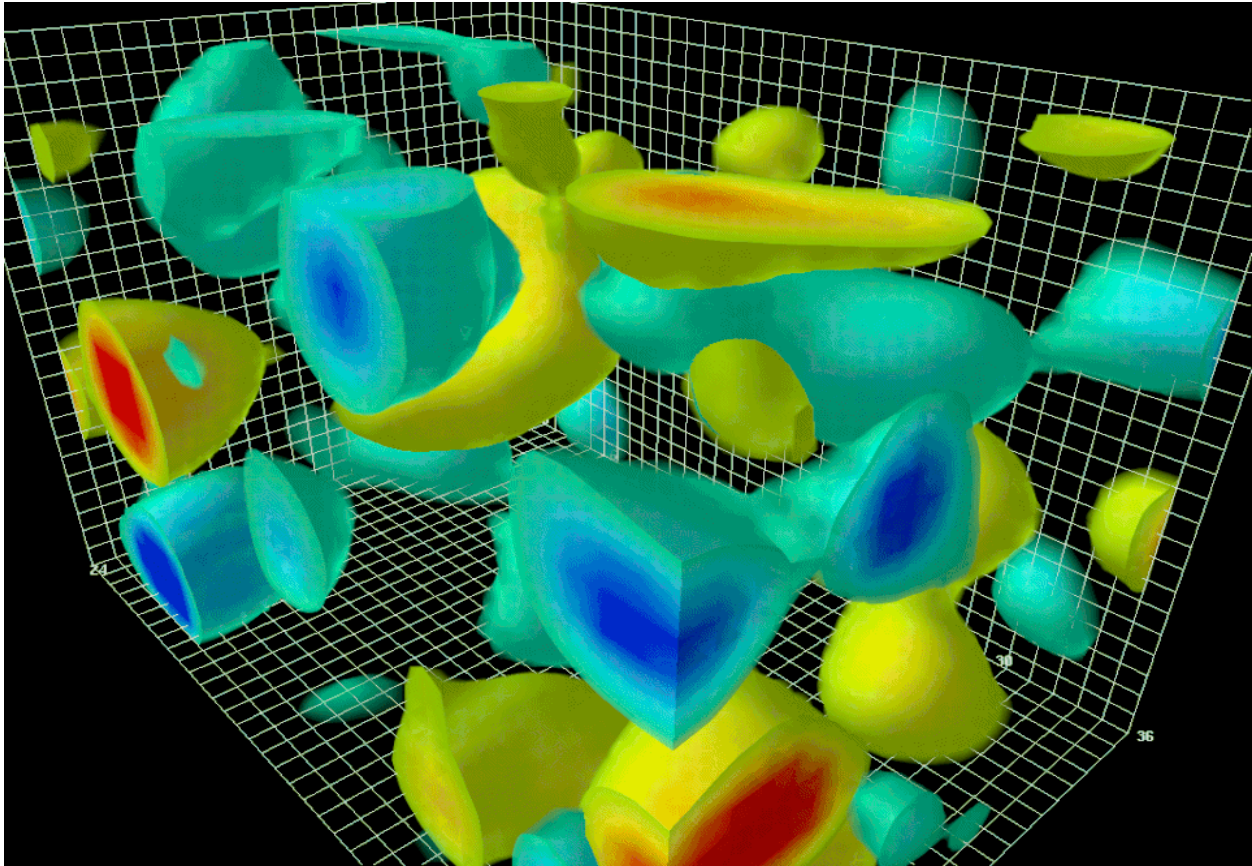
- Perhaps there is a stationary, motionless aether, and as objects moved through it, they experienced length contraction and time dilation, explaining the null result.
- And maybe, just possibly, the same aether that light traveled through, whatever it was, allowed for the propagation of Newton's gravitational force as well.

All of these possibilities, despite their arbitrary constants and parameters, were seriously considered right up until Einstein's relativity came along. Once the realization came about that the laws of physics should be, and in fact were, the same for all observers in all frames of reference, the idea of an "absolute frame of reference," which the aether absolutely was, was no longer necessary or tenable.

If you allow light to come from outside your environment to inside, you can gain information about the relative velocities and accelerations of the two reference frames. The fact that the laws of physics, the speed of light, and every other observable is independent of your reference frame is strong evidence against the need for an aether.

What all of this means is that the laws of physics don't require the existence of an aether; they work just fine without one. Today, with our modern understanding of not just Special Relativity but also General Relativity — which incorporates gravitation — we recognize that both electromagnetic waves and gravitational waves don't require any sort of medium to travel through at all. The vacuum of space, devoid of any material entity, is enough all on its own.

This doesn't mean, however, that we've disproven the existence of the aether. All we've proven, and indeed all we're capable of proving, is that if there is an aether, it has no properties that are detectable by any experiment we're capable of performing. It doesn't affect the motion of light or gravitational waves through it, not under any physical circumstances, which is equivalent to stating that everything we observe is consistent with its non-existence.



Visualization of a quantum field theory calculation showing virtual particles in the quantum vacuum. (Specifically, for the strong interactions.) Even in empty space, this vacuum energy is non-zero. If there are additional particles or fields beyond what the Standard Model predicts, they will affect the quantum vacuum and will change the properties of many quantities away from their Standard Model predictions. However, the QCD contribution cannot be calculated perturbatively, the way electromagnetism can.

If something has no observable, measurable effects on our Universe in any way, shape or form, even in principle, we consider that “thing” to be physically non-existent. But the fact that there’s nothing pointing to the existence of the aether doesn’t mean we fully understand what empty space, or the quantum vacuum, actually is. In fact, there are a whole slew of unanswered, open questions about exactly that topic plaguing the field today.

Why does empty space still have a non-zero amount of energy — dark energy, or a cosmological constant — intrinsic to it? If space is discrete at some level, does that imply a preferred frame of reference, where that discrete “size” is

maximized under the rules of relativity? Can light or gravitational waves exist without space to travel through, and does that mean there is some type of propagation medium, after all?

As Carl Sagan famously said, “Absence of evidence is not evidence of absence.” We have no proof that the aether exists, but can never prove the negative: that no aether exists. All we can demonstrate, and have demonstrated, is that if the aether exists, it has no properties that affect the matter and radiation that we actually do observe, and so the burden isn’t on those looking to disprove its existence: the burden of proof is on those who favor the aether, to provide evidence that it truly is real.

Historic Dispute: Is space filled with a medium known as the aether

Historic Dispute: Is space filled with a medium known as the aether?

Viewpoint: Yes, prior to the twentieth century, many scientists believed in the existence of the aether.

Viewpoint: No, only with [Albert Einstein](#)'s work in the early twentieth century did most scientists accept that the aether did not exist.

The nature of light and the possible existence of a vacuum have been subjects of philosophical speculation since the time of the ancient Greeks. Aristotle argued for the impossibility of a true vacuum, and the first efficient air pump was not developed until the time of [Robert Boyle](#) (1627-1691). While the ancients had acquired some practical knowledge of optics, the modern theory of light and color began with the work of the Dutch scientist [Christiaan Huygens](#) (1629-1693) and the English scientist [Sir Isaac Newton](#) (1642-1727).

Huygens demonstrated how the reflection of light could be understood geometrically if light were treated as a wave traveling at finite speed. Newton claimed that light was the flow of particles. Boyle had demonstrated that sound could not travel through a vacuum, though light passed without difficulty. That observation, together with Newton's immense scientific prestige, worked against the wave hypothesis.

The wave character of light became more credible after [Thomas Young](#) (1733-1829) established that light waves could interfere

with each other, and after the discovery of the [polarization of light](#)—which proved that light was a transverse wave—by the young French experimenter Etienne-Louis Malus (1775-1812) in 1808. Since sound waves, water waves, and waves traveling down a taut string all clearly require the vibration of a medium, it was only natural to assume that light waves were of the same character. Since light travels through a vacuum and through interplanetary space, it was thought that the light-carrying medium or luminiferous aether (sometimes spelled "ether") had to permeate all space. Attempts to assign mechanical properties to the aether were beset with problems. Because light traveled with immense speed and was a transverse wave, the aether had to be extremely rigid and solid rather than fluid. On the other hand, it apparently offered no resistance to the motions of the moon and planets.

The connection between light and electromagnetic phenomena was established by the Scottish mathematical physicist [James Clerk Maxwell](#) (1831-1879) in his *Treatise on [Electricity and Magnetism](#)*, published in 1873. Maxwell showed that the experimental results observed in the laboratory for systems of stationary charges and electrical currents could be summarized in a set of differential equations satisfied by the components of the electric and magnetic field. Maxwell's equations had solutions that described mutually transverse electric and magnetic waves traveling together through space with a speed that could be calculated from the force constants for the electrostatic and magnetic force, which in turn could be determined in the laboratory. Maxwell's theory received wide acceptance and underlined for physicists the importance of better understanding the aether, which was now apparently involved in electrical and magnetic phenomena as well as optical ones.

If an aether existed, it would also provide an absolute frame of reference for motion. As Earth completes its nearly circular orbit of the Sun, it should experience an "ether wind," the velocity of which would vary from one season to another. Light traveling in the direction of this wind and light traveling at right angles to it would then move at different speeds. Detecting the difference in speed was the basis of the Michelson experiment of 1881, later repeated more carefully as the Michelson-Morley experiment. The latter showed at most a small effect.

The inconclusive result of the Michelson-Morley experiment did not in itself spell the demise of the aether theory. Instead of the aether being perfectly stationary, perhaps Earth dragged a certain amount with it as it moved. Possibly the act of moving through the aether affected the measuring instruments.

It is generally considered that the special theory of relativity, as published by [Albert Einstein](#) in 1905, demonstrated the aether did not exist. What Einstein showed, however, was that an entirely consistent physics could be developed in which all observers in uniform motion with respect to each other would measure the same value for the speed of light, regardless of the speed with which they observed the light source to be moving. Einstein's theory met with a certain amount of opposition, in part because it did away with any need for a space-filling aether, but it gained general acceptance after observations made during a solar eclipse confirmed the effect the Sun's motion had on gravitational fields, as predicted by the expanded form of the theory published in 1912.

Twentieth-century physics was also forced to revisit the question as to the wave or particle nature of light. In 1901 [Max Planck](#) (1858-1947) proposed that the energy of a light wave could only increase or decrease by finite amounts, which came to be called *quanta*. In 1905 Einstein explained the

characteristics of the [photoelectric effect](#), the emission of electrons from a metal surface when exposed to light, as the transfer of quanta of energy from the electromagnetic field to single electrons. The quanta of light energy came to be thought of as particle-like "photons." Further insight into the particle properties of light was gained in the discovery of the Compton effect, in which electrons and x-ray photons collide, exchanging energy and momentum; and in the process of pair production, in which a high-energy photon is converted into an electron-positron pair.

While relativity theory made it possible to consider the existence of a totally empty region of space, the quantum field theory—developed to explain the interaction of high-energy particles with the electromagnetic field—requires that the vacuum be thought of as anything but empty on the shortest time scales. In fact, the vacuum is treated as a place where electron-positron and other particle-antiparticle pairs come momentarily into existence and disappear. The propagation of electromagnetic fields through empty space is aided by the so-called vacuum polarization that results from the behavior of these "virtual" pairs, which might in a sense constitute the latest incarnation of the aether.

Viewpoint: Yes, prior to the twentieth century, many scientists believed in the existence of the aether.

The belief in the aether (or ether) that was prominent in the nineteenth century is often described in scornful and derisive tones. The search for the aether, and the disbelief when it was not found, is often ridiculed, and portrayed as one of the follies of modern science. Yet there were very good scientific reasons for supposing the existence of a substance through which light

could travel. The famous 1887 Michelson-Morley experiment was not as cut and dried as is often portrayed in the literature, and the controversy over the existence of the aether raged for decades after it was performed.

Early Studies of the Aether

The aether is a hypothesized substance that allows the transmission of light throughout the universe. Its existence was postulated as far back as the ancient Greek philosophers, who offered a number of speculative theories on the nature of light and sight. The existence of the aether was seemingly set in stone when both René Descartes (1596-1650) and Isaac Newton (1642-1727) used it in their competing scientific philosophies. Descartes proposed a mechanical universe filled with matter, which he called the plenum, which was for all purposes the aether by another name. Newton was more cautious about the existence of the aether, but speculated that it filled the whole universe, and acted as "God's Sensorium," the means by which the universe was controlled. Newton's followers considered the aether essential, as it provided a stationary frame of reference for the laws of motion.

While both Descartes and Newton had used the aether mainly for philosophical reasons, there was some experimental support for the substance. In the 1660s [Robert Boyle](#) (1627-1691) succeeded in showing that the ringing of a bell could not be heard inside a vacuum. However, while sound was silenced in a vacuum, you could still see through it. Obviously, while sound required air to propagate, light did not. This suggested a more subtle substance than air was inside the supposed vacuum, and it was naturally assumed that it was the aether. This theory, by removing the notion of a complete vacuum, something that was unthinkable to many, found strong support.

Newton claimed that light was corpuscular in nature, consisting of tiny particles moving at infinite speed. However, at about the same time Christian Huygens (1629-1695) proposed that light was composed of waves, and that it had a finite speed. Waves travel through a medium, for example, a ripple in a pond moves through the water, and sound results from the vibrations of a body disturbing the air. It seemed only natural to assume that if light was a wave it must also travel through some sort of medium. Newton's corpuscular theory was dominant at first, but in the nineteenth century there were many experimental results that could only be explained if light was indeed a wave. The existence of the aether seemed more logical than ever.

Many properties of a wave are determined by the medium through which it travels. The mathematical relationship between pitch and tension in a piece of string has been known since the time of Pythagoras (sixth century b.c.). Galileo (1564-1642) refined the concept to relate to specific frequencies of vibration. The speed of the vibrations passing through a substance move more rapidly if the substance is stiffer. The speed a wave travels down a rope depends on the rope's tension and mass. The more tension or lighter the rope, the faster the wave travels. As details about the nature of light began to be found experimentally it became possible to work backwards and deduce the nature of the aether.

As early as 1746 [Leonhard Euler](#) (1707-1783) calculated that the density of the aether must be at least a hundred million times less than that of air, but its elasticity had to be a thousand times greater, making it more rigid than steel. In the 1840s it was proposed that the aether was an elastic-fluid, a theory that helped explain the phenomenon of double refraction, as well as circular polarization, and some thermodynamics problems. However, the work of [Thomas Young](#) (1773-1829), Augustin

Fresnel (1788-1827), and François Arago (1786-1853) showed that light waves were transverse, not longitudinal as previously supposed. Transverse waves were unknown in any fluid medium, so the aether was therefore logically limited to being a solid rigid enough to allow the high speed of light waves to be transmitted, yet somehow offering no resistance to the motion of larger objects such as the planets, as the Newtonian laws of mechanics satisfactorily explained the motion of the planets. It was suggested that the aether was a stiff jelly-like substance that would act as solid for vibrations, but allow the easy passage of large objects.

Despite the growing uneasiness in the strangeness of the aether, there was further support for its existence in 1850 when Armand Fizeau (1819-1896) and Jean Leon Foucault (1819-1868) revealed that light travels more slowly in water than in air, confirming that it travels as a wave, and that its wavelength is decreased in the medium of water. Fizeau also showed that the velocity of light can be sped up or slowed down by making the water flow with or against the light. The work of [Michael Faraday](#) (1791-1867) and [James Clerk Maxwell](#) (1831-1879) united electricity, magnetism, and light, and the aether became the proposed medium for magnetic force as well, yet appeared to have no other properties.

Michelson-Morley Experiment

Towards the end of the nineteenth century a number of experiments were performed to measure the relative motion of Earth to the aether. In 1881 Albert Michelson (1852-1931) attempted to measure Earth's speed through the aether using a sensitive measuring device developed by Michelson called an interferometer. It is often erroneously stated that the purpose of the experiment was to determine the existence of the aether. Michelson assumed the aether existed, and was only

attempting to measure the expected effects it would produce. However, the experiment failed to produce the expected results.

It is also erroneously reported in many histories that this experiment, and the later refinements, showed no changes in speed in any direction. However, this first "null" result did actually find some change in the interference pattern, as did all the later tests, but the effect was so small as to fall within [experimental error](#). Various reasons were proposed for the lack of a result, from errors in the experimental setup, to the possibility that the jelly-like aether was dragged along with Earth as it moved. No one seriously suggested that the aether might not exist.

While Michelson was satisfied that his interferometer was extremely precise, he nevertheless attempted to refine his technique. Teaming up with Edward Morley (1838-1923), who had a background in precise measurements, they repeated the interferometer experiment, and also confirmed Fizeau's experiment regarding the change in the speed of light in a flow of water. In 1887 they published another "null" result, stating that the change in the interference pattern was far too small to account for a stationary aether.

While many histories of science hail the 1887 result as a turning point in physics, and see it as the death of the aether, neither Michelson, Morley, or the wider scientific community of the time perceived the results in that way. Again, many plausible reasons were given for the result, all of which assumed the existence of the aether. There was simply too much previous evidence for the aether to allow one experiment to overthrow it. That same year Heinrich Hertz (1857-1894) demonstrated the first wireless transmission of electronic waves, helping to begin the radio revolution and providing strong support to the

existence of the aether as a combined electromagnetic medium for light, magnetic, and electric waves.

The most promising explanation for the Michelson-Morley result was that Earth dragged a portion of the aether along with it as it traveled, hereby reducing the effective relative motion.

However, Sir Oliver Lodge (1851-1940) performed an experiment that showed that this was not the case. Others, such as Sir George Stokes, insisted the aether-drag hypothesis was correct, as it explained a number of other optical phenomena.

Another explanation was provided by George Fitz Gerald (1851-1901) and Hendrick Lorentz (1853-1928) who both independently suggested that the experimental setup might shrink in the direction of Earth's movement. Maxwell had shown earlier that the force between two electric charges depends on how they are moving. FitzGerald and Lorentz suggested that the electromagnetic forces inside a solid may therefore contract by one part in a hundred million if moving in the direction of Earth's orbit. In the 1890s Lorentz calculated the transformations, which describe the length of a moving object, and its contraction when viewed by an observer at various speeds.

In 1905 Morley collaborated with Dayton Miller (1866-1941) to refine the aether experiment. While it returned a "very definite positive effect," it was still far too small to match the expected values of Newtonian physics. Then, that same year, Albert Einstein (1879-1955) published his special theory of relativity, which implied that there was no need for the mysterious and undetectable aether. All of the current experimental contradictions could be explained away by the new theory, and the aether could be forgotten.

Aether and the Theory of Relativity

Relativity was not widely accepted at first, and one of the reasons for the strong resistance to it was the cherished notion of the aether. There were many eminent scientists of the time who refused to believe that waves could travel without a medium to propagate through. Such an idea went against centuries of scientific authority and experimental evidence. It was not until after [World War I](#) that a direct observational experiment of relativity could be made, when the light of stars behind the Sun was shown to be bent by the Sun's gravity during a solar eclipse. Relativity was pronounced triumphant, and support for the undetectable aether dwindled.

Einstein had been greatly influenced by the Lorentz transformations, but he admitted that he did not seriously consider the Michelson-Morley experiment, as it was only one of a whole series of puzzling aether experiments that had been done in the nineteenth century. Yet the Michelson-Morley experiment became one of the most celebrated means of explaining the ideas of relativity theory to the wider scientific community. Over time it became accepted that the experiments had been about proving or disproving the existence of the aether, and had formed a crucial logical step towards the theory of relativity.

In 1920 Einstein gave a speech titled "Aether and Relativity Theory" to an audience in Germany. Surprisingly the speech assumed the existence of the aether, even going so far as to say "space without ether is unthinkable." However, Einstein's aether was a far different substance than the strange solid-fluid substance that had proved to be impossible to find. Yet that old concept of the aether survived in many circles, and in 1920 Miller began a further series of aether experiments. In 1925 Miller announced that he had found a consistent, but small,

positive result over many years, and he concluded that "there is a relative motion of the earth through the ether," contrary to relativity. Michelson and many others immediately began experiments of their own, none of which found positive results, and by 1929 even Miller was conceding that his results may have been in error.

The aether was consigned to the same fate of such other hypothesized substances as phlogiston and caloric and magnetic effluvia. Over time those who had championed the aether have become something of a laughing stock, and the story of the search for the aether is told as though it was folly. However, there were many good logical and scientific reasons for thinking the aether existed. Throughout the nineteenth century a number of key experimental results were obtained that seemed most easily explained by a electromagnetic medium. The controversial nature of many of the so-called "null" results in the aether-drift experiments did not immediately suggest the non-existence of the aether, and a number of innovative, but logical, explanations for the Michelson-Morley results were given, some of which helped inspire relativity theory. The aether was shown to be undetectable and unnecessary, however, that does not imply that it may not exist. There may indeed be a substance that acts as a medium for the transmission of light that has no other properties. [John Bell](#) (1928-1990), a mathematical physicist, even proposed that the theory of the aether be revived as a solution to a dilemma in quantum physics—although perhaps only half-seriously. The aether is still occasionally invoked by inventors of impossible perpetual motion machines and free-energy devices, but it should be remembered that it once had the support of solid evidence and logical arguments, and it only disappeared from scientific thought after many years of debate and experiment

showed that it was simpler to abandon the medium than explain its weird properties and lack of detectability.

Viewpoint: No, only with Albert Einstein's work in the early twentieth century did most scientists accept that the aether did not exist.

In the opening years of the twentieth century, the study of light was the central concern of most leading physicists. Mainstream physics agreed that light consisted of electro-magnetic waves, moving through a substance called the *aether*. However, the precise nature of the aether had not been identified and the resolution of this problem was regarded as the major task for physics in the new century. Then, due to his musings on the significance of the speed of light, Albert Einstein (1879-1955) developed a revolutionary framework for thinking about the relationship between space and time. In a few years, the special theory of relativity, as this framework was called, had changed the focus of physics. This transformed the understanding of light. Einstein showed that the aether, and the notion of absolute space and time that it represented, did not exist. The aether gradually ceased to be of any interest to the mainstream of inquiry in the physical sciences. Einstein's work on the [photoelectric effect](#) also transformed the understanding of light waves. This led to the idea of wave-particle duality as a way of characterizing the nature of light in different situations.

Ad ends in 1

Waves of Light

Prior to the nineteenth century, the mainstream of scientific thought regarded light as streams of tiny particles. This was the position of [Sir Isaac Newton](#) (1642-1727), whose authority had an enormous influence on all fields of scientific endeavor. It was

not until the nineteenth century that serious consideration began to be given to the idea that light might consist of waves rather than particles. Successive experiments by physicists found that the wave theory best explained the behavior of light. The work of the British physicist James Maxwell (1831-1879) on electro-magnetic phenomena further strengthened this approach. Maxwell developed equations to describe the behavior of electro-magnetic phenomena. Thus, he was able to calculate the speed at which electro-magnetic waves moved in a vacuum, which coincided with the velocity of light. From this, Maxwell concluded that light was waves of oscillating electro-magnetic charges.

The Luminiferous Aether

The triumph of the wave theory of light made the aether the center of attention. The aether had a long history in philosophical thought about the nature of the universe. It was believed to be the substance that filled up the realms of celestial space and was often identified as the mysterious fifth element, along with air, water, earth, and fire, the basis of all matter. The aether acquired additional significance in the nineteenth century, with its emphasis upon a mechanical approach in which all events could be attributed to local causes. Nineteenth-century physicists were opposed to the idea of action at a distance, the idea that an object at one point could affect an object at another point with no medium for the effect. For a lighted candle to influence another object, such as the human eye, there had to be something that could transmit the influence from one point to another. If light was a wave, it required a medium to move through. As it had been observed that light traveled through a vacuum, it was concluded that whatever the medium of light was, it was even thinner than air. The aether,

the mysterious substance that filled space, was identified as the *luminiferous medium*.

Therefore, to understand light, it was necessary to understand the special characteristics of the light medium. Many physicists developed complex models in order to try and describe the aether, but none of these were able to capture its special and apparently contradictory qualities. The aether had to be very thin and elastic, so that solid objects, such as the earth, could pass through it without resistance. At the same time, it had to be very dense to allow for the transmission of the vibration of light from one part of the aether to the next at such high speeds. For the last two decades of the nineteenth century, the attempt to accurately describe the aether occupied some of the best minds in physics.

The Aether and Absolute Space

One of the most crucial issues regarding the aether was the question of its immobility. Most physicists regarded the aether as fixed and stagnant, completely stationary. Objects might move through it, but no part of the aether was moving, relative to any other part. It stretched throughout space, acting as a framework against which the movement of light could be studied and measured. In this sense, the aether can be identified with the concept of absolute space. Most of the statements made about the movement of objects in the universe were relative; Earth was moving at a certain speed relative to the Moon, or another moving planetary object. Yet nineteenth-century science had at its foundation the idea of absolute space and time, a fixed reference system in nature from which Earth's absolute velocity could be measured. All movement in the universe was therefore movement relative to this stationary system. However, given that we participate in Earth's movement through the universe, some people were

skeptical about the possibility of being able to step outside this and gain knowledge of our absolute position in the universe. As James Maxwell so eloquently wrote: "There are no landmarks in space; one portion of space is exactly like every other portion so that we cannot tell where we are. We are, as it were, on an unruffled sea, without stars, compass, soundings, wind or tide, and we cannot tell in what directions we are going. We have no log which we can cast out to take a reckoning by; we may compare our rate of motion with respect to the neighboring bodies, but we do not know how these bodies may be moving in space."

The Michelson-Morley Experiment

However, not everyone shared this vision of humanity hurtling blindly through space. Many believed that the aether provided a fixed reference system against which all motion could be measured. Two American scientists, Albert Michelson (1852-1931) and Edward Morley (1838-1923), constructed a machine that could theoretically discern the speed of Earth through the aether. The Michelson-Morley experiment was set up to measure the impact of the aether drift on the velocity of light. The aether drift was the wind that was created by the velocity of Earth through the motionless aether, just as a person traveling in a car on a still day feels a wind if he or she put a hand out the window. Michelson reasoned that this wind should have an effect on the speed of light. He set up a machine that constructed a race between two rays of light, one moving in the same direction that Earth was moving, and the other in a perpendicular direction. The effect of the aether drift meant that one ray of light should reach the finish line before the other. The difference in time would be incredibly small, but Michelson devised a machine, based on earlier experiments, called an

interferometer, that was sensitive enough to be able to measure the difference.

However, the experiment produced a null result. The rays of light were unaffected by the aether drift. This suggested that, relative to the aether, Earth was not moving at all. It was as if the car you were in was traveling at 40 mph (70 kph), but you could not feel the wind that should have been created by the velocity of the vehicle. This result was puzzling, because so much of what scientists knew about the movement of light depended upon the existence of the aether drift. Once again, the mysterious aether had appeared to evade detection. A variety of different explanations were developed that tried to account for Michelson and Morley's results. However, until Einstein, none directly questioned the existence of the aether itself. Conceptually, it was too fundamental to the fabric of physics as a medium for the movement of electro-magnetic phenomena.

One physicist who was particularly interested in the significance of the result of the Michelson-Morley experiment was H. A. Lorentz. (1853-1928) Through his calculations on the behavior of small electrically charged particles, Lorentz observed that their mass changed as they moved through the aether. Therefore, Earth's velocity through the aether caused a contraction in matter that was positioned parallel to Earth's movement. In the case of the Michelson-Morley experiment, everything that was traveling into the aether wind was contracted. This contraction canceled out the disadvantage of racing into the wind, producing the null result. Lorentz admitted that this theory was "very startling." However, he managed to incorporate these conclusions within the traditional framework of physics, retaining the importance of the aether as the fixed

reference system against which to measure the movement of electro-magnetic phenomena.

Einstein and the Aether

In 1905, Albert Einstein considered the problem from a different angle. The issue of the movement through the aether was not his prime concern. Instead, Einstein's theories were produced out of his consideration on the contradictions between two apparently valid principles. The first was the Galilean principle of relativity, which says that the laws regarding motion are the same regardless of the frame of reference. In other words, whether you are in a car traveling at a uniform speed of 100 kph, or in a train traveling at 10 kph, the laws of motion are the same in both cases. The second principle stems from Maxwell's equations, which established the law that light in a vacuum always moves with a velocity $c = 300,000\text{km/sec}$. According to the principle of relativity then, this must be the speed of light in all circumstances, whether it is measured in a car or on a train, regardless of the speed at which these are moving. Within the existing framework of physics, this was impossible, because the speed of anything always depended upon the framework from which it was being measured. For instance, the speed of the car might be 100 kph as measured from the roadside, but it will only be 90 kph measured from a train traveling parallel in the same direction at 10 kph. The same should apply to light. Therefore, either the principle that states the speed of light, or the principle of relativity, had to be incorrect.

However, Einstein found that the problem lay with the concept of absolute space and time. The old approach assumed that space and time were the same for all observers. Between any two events, say the firing of a pistol and the bullet striking its target, there would be a spatial separation, perhaps 80 ft (25 m), and a time interval, perhaps 0.04 seconds, which all

observers would agree on. Einstein was able to show that this was not the case; the observed spatial separation of and time interval between the events depend on the reference frame of the observer. By eliminating the assumptions of absolute space and time, Einstein was able to develop a consistent physics in which the speed of light was always c , regardless of the frame of reference. This resolved the apparent contradiction that had so troubled him. These calculations exactly mirrored those that Lorentz had earlier devised in his observations, but Einstein was the first to recognize their true significance for ideas about space and time. These conclusions form the basis of what is known as the special theory of relativity.

The relativity of space and time had enormous consequences for the role of the aether in physics. Einstein's statement at the beginning of his 1905 paper "On the Electrodynamics of Moving Bodies" indicates this. "The introduction of a Light aether will prove to be superfluous, for according to the conceptions which will be developed, we shall introduce neither a space absolutely at rest, and endowed with special properties...." There was no fixed point, no stationary reference system within this new vision of the universe; everything was in movement relative to each other. As Einstein points out, the result of the Michelson-Morley experiment will always be null. "According to this theory there is no such thing as a 'specially favored' (unique) co-ordinate system to occasion the introduction of the aether-idea, and hence there can be no aether-drift, nor any experiment with which to demonstrate it." In other words, the Michelson-Morley experiment kept getting a null result because they were measuring the velocity of Earth against something that did not exist. Because of this shift away from notions of absolute space and time, it was gradually recognized that the aether, or any kind of medium for light, was unnecessary.

Einstein and Photons

Einstein's work in 1905 was also significant for light in other respects. The wave theory of light appeared to have triumphed over the particle theory in the nineteenth century. But Einstein's work on the photoelectric effect showed that the wave theory was by itself insufficient to explain the behavior of light. He reintroduced the notion of particles of light into the vocabulary of physics, but this time in a much more sophisticated way. In terms of its interaction with matter, Einstein suggested light was composed of particles of energy. These particles interacted with matter, and could eject electrons from their original positions. The development of the idea of light photons, as they came to be known, challenged the earlier dichotomy between theories of light based on particles or waves. Whether the concept of light as a wave or as a particle is more appropriate depends on the context of what is being observed. The two models complement each other, and this is referred to as wave-particle duality.

Conclusion

Einstein's work on light went beyond classical physics in two respects. He eliminated the need for the aether as the light medium, and he demonstrated that the description of light as a wave was inadequate to explain all the characteristics of light. As in most cases, the publication of Einstein's work in 1905 did not cause a sudden rupture with earlier ideas. The full ramifications were not immediately apparent to all, and many physicists ignored his work and carried on with their own research into the aether. But gradually, the impact began to filter through the profession of physics, and the cutting edge of physics was inquiry based on these new ideas. The aether was firmly tied to the most basic assumptions of nineteenth-century

physics. With the death of absolute space, it ceased to be of any interest to most mainstream physicists.

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KEY TERMS

AETHER DRIFT:

The relative movement of Earth and the aether. The velocity of Earth through the stagnant aether creates an aether drift.

ELECTROMAGNETIC WAVE:

A system of electric and magnetic fields traveling together in space.

LONGITUDINAL WAVE:

The medium is displaced in line or parallel to the direction of travel, causing compressions and rarefactions. Sound waves in air are longitudinal.

PHOTOELECTRIC EFFECT:

Release of electrons from an object exposed to [electromagnetic radiation](#).

PHOTON:

Particle of [electromagnetic radiation](#).

RELATIVITY:

The theory that the distances and time intervals measured by an observer depend on the state of motion of the observer in such a way that all observers measure the speed of light in vacuum to have the same value, regardless of the motion of the light source.

TRANSVERSE WAVE:

Where the displacement of the medium occurs at right angles to the direction of travel of the wave motion. For example, a vibrating string, or ripples in a pond.

VACUUM:

Space in which there is very few atoms or molecules.

WAVE-PARTICLE DUALITY:

Light can be described as both consisting of electromagnetic waves, and particles of energy. Which description is more

appropriate depends upon what aspect of light is being described.

ALBERT EINSTEIN AND THE NOBEL PRIZE

Albert Einstein was awarded the [Nobel Prize](#) for physics in 1921. That he received the prize was not surprising. By this time, the [general theory of relativity](#), which applied his ideas about the relativity of space and time to the problem of gravity, had been confirmed by observational data. As a result, Einstein had achieved worldwide fame and was recognized as one of the greatest minds in the history of science. Indeed, the fact that he was going to receive a [Nobel Prize](#) was so widely anticipated that in 1919 the expected prize money for the award was included as part of his divorce settlement with his wife.

However, what is surprising is that Einstein was not awarded the Nobel Prize for his most famous achievement. His citation states that he received the prize "for services to theoretical physics, and especially for his discovery of the photoelectric effect." There was no direct mention of the special and [general theory of relativity](#), which had gained him celebrity status and for which he is still best known today. The reason for this indicates something about the nature of the Nobel Prize and about the wider reception of Einstein's theory. In 1895, the Swedish industrialist Alfred Nobel had left provision for the Nobel Prize in his will, which specified that part of his fortune should be "distributed in the form of prizes to those who, during the preceding years, shall have conferred the greatest benefit on mankind." Theoretical physics was not strong in Sweden at this time, and to those judging the prize, the significance of the theory of relativity to "the greatest benefit of mankind" was not clear. It seemed more in keeping with the spirit of Nobel's instructions to cite a part of Einstein's work, such as his

discovery of the photoelectric effect, that appeared to have obvious practical applications. Therefore, while it is the special and general theory of relativity that has granted Einstein a degree of immortality, at the time it was not regarded as appropriate for a Nobel Prize.

Luminiferous Aether

Luminiferous aether or ether ("luminiferous", meaning "light-bearing") was the postulated medium for the propagation of light. It was invoked to explain the ability of the apparently wave-based light to propagate through empty space, something that waves should not be able to do. The assumption of a spatial plenum of luminiferous aether, rather than a spatial vacuum, provided the theoretical medium that was required by wave theories of light. The aether hypothesis was the topic of considerable debate throughout its history, as it required the existence of an invisible and infinite material with no interaction with physical objects. As the nature of light was explored, especially in the 19th century, the physical qualities required of an aether became increasingly contradictory. By the late 1800s, the existence of the aether was being questioned, although there was no physical theory to replace it. The negative outcome of the Michelson-Morley experiment (1887) suggested that the aether did not exist, a finding that was confirmed in subsequent experiments through the 1920s. This led to considerable theoretical work to explain the propagation of light without an aether. A major breakthrough was the theory of relativity, which could explain why the experiment failed to see aether, but was more broadly interpreted to suggest that it was not needed. The Michelson-Morley experiment, along with the blackbody radiator and photoelectric effect, was a key experiment in the development of modern physics, which includes both relativity and quantum theory, the latter of which explains the particle-like nature of light.

physical theory physical qualities photoelectric

1. The History of Light and Aether

1.1. Particles vs. Waves

In the 17th century, Robert Boyle was a proponent of an aether hypothesis. According to Boyle, the aether consists of subtle particles, one sort of which explains the absence of vacuum and the mechanical interactions between bodies, and the other sort of which explains phenomena such as magnetism (and possibly gravity) that are, otherwise, inexplicable on the basis of purely mechanical interactions of macroscopic bodies, "though in the ether of the ancients there was nothing taken notice of but a diffused and very subtle substance; yet we are at present content to allow that there is always in the air a swarm of steams moving in a determinate course between the north pole and the south".^[1]

Christiaan Huygens's *Treatise on Light* (1690) hypothesized that light is a wave propagating through an aether. He and Isaac Newton could only envision light waves as being longitudinal, propagating like sound and other mechanical waves in fluids. However, longitudinal waves necessarily have only one form for a

given propagation direction, rather than two polarizations like transverse wave. Thus, longitudinal waves can not explain birefringence, in which two polarizations of light are refracted differently by a crystal. In addition, Newton rejected light as waves in a medium because such a medium would have to extend everywhere in space, and would thereby "disturb and retard the Motions of those great Bodies" (the planets and comets) and thus "as it [light's medium] is of no use, and hinders the Operation of Nature, and makes her languish, so there is no evidence for its Existence, and therefore it ought to be rejected".

Isaac Newton contended that light is made up of numerous small particles. This can explain such features as light's ability to travel in straight lines and reflect off surfaces. Newton imagined that light particles as non-spherical "corpuscles", with different "sides" that give rise to birefringence. But the particle theory of light can not satisfactorily explain refraction and diffraction. To explain refraction, Newton's Third Book of *Opticks* (1st ed. 1704, 4th ed. 1730) postulated an "aethereal medium" transmitting vibrations faster than light, by which light, when overtaken, is put into "Fits of easy Reflexion and easy Transmission", which caused refraction and diffraction. Newton believed that these vibrations were related to heat radiation:

Is not the Heat of the warm Room convey'd through the vacuum by the Vibrations of a much subtiler Medium than Air, which after the Air was drawn out remained in the Vacuum? And is not this Medium the same with that Medium by which Light is refracted and reflected, and by whose Vibrations Light communicates Heat to Bodies, and is put into Fits of easy Reflexion and easy Transmission?^{[2]:349}

In contrast to the modern understanding that heat radiation and light are both electromagnetic radiation, Newton viewed heat and light as two different phenomena. He believed heat vibrations to be excited "when a Ray of Light falls upon the Surface of any pellucid Body".^{[2]:348} He wrote, "I do not know what this Aether is", but that if it consists of particles then they must be

exceedingly smaller than those of Air, or even than those of Light: The exceeding smallness of its Particles may contribute to the greatness of the force by which those Particles may recede from one another, and thereby make that Medium exceedingly more rare and elastic than Air, and by consequence exceedingly less able to resist the motions of Projectiles, and exceedingly more able to press upon gross Bodies, by endeavoring to expand itself.^{[2]:352}

1.2. Bradley Suggests Particles

In 1720, James Bradley carried out a series of experiments attempting to measure stellar parallax by taking measurements of stars at different times of the year. As the Earth moves around the sun, the apparent angle to a given distant spot changes. By measuring those angles the distance to the star can be calculated based on the known orbital circumference of the Earth around the sun. He failed to detect any parallax, thereby placing a lower limit on the distance to stars.

During these experiments, Bradley also discovered a related effect; the apparent positions of the stars did change over the year, but not as expected. Instead of the apparent angle being maximized when the Earth was at either end of its orbit with respect to the star, the angle was maximized when the Earth was at its fastest sideways velocity with respect to the star. This effect is now known as stellar aberration.

Bradley explained this effect in the context of Newton's corpuscular theory of light, by showing that the aberration angle was given by simple vector addition of the Earth's orbital velocity and the velocity of the corpuscles of light, just as vertically falling raindrops strike a moving object at an angle. Knowing the Earth's velocity and the aberration angle, this enabled him to estimate the speed of light.

Explaining stellar aberration in the context of an aether-based theory of light was regarded as more problematic. As the aberration relied on relative velocities, and the measured velocity was dependent on the motion of the Earth, the aether had to be remaining stationary with respect to the star as the Earth moved through it. This meant that the Earth could travel through the aether, a physical medium, with no apparent effect – precisely the problem that led Newton to reject a wave model in the first place.

1.3. Wave-Theory Triumphs

A century later, Thomas Young^[3] and Augustin-Jean Fresnel revived the wave theory of light when they pointed out that light could be a transverse wave rather than a longitudinal wave; the polarization of a transverse wave (like Newton's "sides" of light) could explain birefringence, and in the wake of a series of experiments on diffraction the particle model of Newton was finally abandoned. Physicists assumed, moreover, that like mechanical waves, light waves required a medium for propagation, and thus required Huygens's idea of an aether "gas" permeating all space.

However, a transverse wave apparently required the propagating medium to behave as a solid, as opposed to a gas or fluid. The idea of a solid that did not interact with other matter seemed a bit odd, and Augustin-Louis Cauchy suggested that perhaps there was some sort of "dragging", or "entrainment", but this made the aberration measurements difficult to understand. He also suggested that the *absence* of longitudinal waves suggested that the aether had negative compressibility. George Green pointed out that such a fluid would be unstable. George Gabriel Stokes became a champion of the entrainment interpretation, developing a model in which the aether might be (by analogy with pine pitch) rigid at very high frequencies and fluid at lower speeds. Thus the Earth could move through it fairly freely, but it would be rigid enough to support light.

1.4. Electromagnetism

In 1856, Wilhelm Eduard Weber and Rudolf Kohlrausch measured the numerical value of the ratio of the electrostatic unit of [charge](#) to the electromagnetic unit of charge. They found that the ratio equals the product of the speed of light and the square root of two. The following year, Gustav Kirchhoff wrote a paper in which he showed that the speed of a signal along an electric wire was equal to the speed of light. These are the first recorded historical links between the speed of light and electromagnetic phenomena.

James Clerk Maxwell began working on Michael Faraday's lines of force. In his 1861 paper *On Physical Lines of Force* he modelled these magnetic lines of force using a sea of molecular vortices that he considered to be partly made of aether and partly made of ordinary matter. He derived expressions for the dielectric constant and the magnetic permeability in terms of the transverse elasticity and the density of this elastic medium. He then equated the ratio of the dielectric constant to the magnetic permeability with a suitably adapted version of Weber and Kohlrausch's result of 1856, and he substituted this result into Newton's equation for the speed of sound. On obtaining a value that was close to the speed of light as measured by Hippolyte Fizeau, Maxwell concluded that light consists in undulations of the same medium that is the cause of electric and magnetic phenomena.^{[4][5][6][7]}

Maxwell had, however, expressed some uncertainties surrounding the precise [nature](#) of his molecular vortices and so he began to embark on a purely dynamical approach to the problem. He wrote another paper in 1864, entitled "A Dynamical Theory of the Electromagnetic Field", in which the details of the luminiferous medium were less explicit.^[8] Although Maxwell did not explicitly mention the sea of molecular vortices, his derivation of Ampère's circuital law was carried over from the 1861 paper and he used a dynamical approach involving rotational motion within the electromagnetic field which he likened to the action of flywheels. Using this approach to justify the electromotive force equation (the precursor of the Lorentz force equation), he derived a wave equation from a set of eight equations which appeared

in the paper and which included the electromotive force equation and Ampère's circuital law.^[8] Maxwell once again used the experimental results of Weber and Kohlrausch to show that this wave equation represented an electromagnetic wave that propagates at the speed of light, hence supporting the view that light is a form of electromagnetic radiation.

The apparent need for a propagation medium for such Hertzian waves can be seen by the fact that they consist of orthogonal electric (E) and magnetic (B or H) waves. The E waves consist of undulating dipolar electric fields, and all such dipoles appeared to require separated and opposite electric charges. Electric charge is an inextricable property of matter, so it appeared that some form of matter was required to provide the alternating current that would seem to have to exist at any point along the propagation path of the wave. Propagation of waves in a true vacuum would imply the existence of electric fields without associated electric charge, or of electric charge without associated matter. Albeit compatible with Maxwell's equations, electromagnetic induction of electric fields could not be demonstrated in vacuum, because all methods of detecting electric fields required electrically charged matter.

In addition, Maxwell's equations required that all electromagnetic waves in vacuum propagate at a fixed speed, c . As this can only occur in one reference frame in Newtonian physics (see Galilean relativity), the aether was hypothesized as the absolute and unique frame of reference in which Maxwell's equations hold. That is, the aether must be "still" universally, otherwise c would vary along with any variations that might occur in its supportive medium. Maxwell himself proposed several mechanical models of aether based on wheels and gears, and George Francis FitzGerald even constructed a working model of one of them. These models had to agree with the fact that the electromagnetic waves are transverse but never longitudinal.

1.5. Problems

By this point the mechanical qualities of the aether had become more and more magical: it had to be a fluid in order to fill space, but one that was millions of times more rigid than steel in order to support the high frequencies of light waves. It also had to be massless and without viscosity, otherwise it would visibly affect the orbits of planets. Additionally it appeared it had to be completely transparent, non-dispersive, incompressible, and continuous at a very small scale. Maxwell wrote in *Encyclopædia Britannica*:^[9]

Aethers were invented for the planets to swim in, to constitute electric atmospheres and magnetic effluvia, to convey sensations from one part of our bodies to another, and so on, until all space had been filled three or four times over with aethers. ... The only aether which has survived is that which was invented by Huygens to explain the propagation of light.

Contemporary scientists were aware of the problems, but aether theory was so entrenched in [physical law](#) by this point that it was simply assumed to exist. In 1908 Oliver Lodge gave a speech on behalf of Lord Rayleigh ^[10] to the Royal Institution on this topic, in which he outlined its physical properties, and then attempted to offer reasons why they were not impossible. Nevertheless, he was also aware of the criticisms, and quoted Lord Salisbury as saying that "aether is little more than a nominative case of the verb *to undulate*". Others criticized it as an "English invention", although Rayleigh jokingly stated it was actually an invention of the Royal Institution.^[11]

By the early 20th century, aether theory was in trouble. A series of increasingly complex experiments had been carried out in the late 19th century to try to detect the motion of the Earth through the aether, and had failed to do so. A range of proposed aether-dragging theories could explain the null result but these were more complex, and tended to use arbitrary-looking coefficients and physical assumptions. Lorentz and FitzGerald offered within the framework of Lorentz ether theory a more elegant solution to how the motion of an absolute aether could be undetectable (length contraction), but if their equations were

correct, the new special theory of relativity (1905) could generate the same mathematics without referring to an aether at all. Aether fell to Occam's Razor.^{[4][5][6][7]}

2. Relative Motion Between the Earth and Aether

2.1. Aether Drag

The two most important models, which were aimed to describe the relative motion of the Earth and aether, were Augustin-Jean Fresnel's (1818) model of the (nearly) stationary aether including a partial aether drag determined by Fresnel's dragging coefficient,^[12] and George Gabriel Stokes' (1844)^[13] model of complete aether drag. The latter theory was not considered as correct, since it was not compatible with the aberration of light, and the auxiliary hypotheses developed to explain this problem were not convincing. Also, subsequent experiments as the Sagnac effect (1913) also showed that this model is untenable. However, the most important experiment supporting Fresnel's theory was Fizeau's 1851 experimental confirmation of Fresnel's 1818 prediction that a medium with refractive index n moving with a velocity v would increase the speed of light travelling through the medium in the same direction as v from c/n to:^{[14][15]}

$$cn + (1 - n^2)v.$$

That is, movement adds only a fraction of the medium's velocity to the light (predicted by Fresnel in order to make Snell's law work in all frames of reference, consistent with stellar aberration). This was initially interpreted to mean that the medium drags the aether along, with a *portion* of the medium's velocity, but that understanding became very problematic after Wilhelm Veltmann demonstrated that the index n in Fresnel's formula depended upon the wavelength of light, so that the aether could not be moving at a wavelength-independent speed. This implied that there must be a separate aether for each of the infinitely many frequencies.

2.2. Negative Aether-Drift Experiments

The key difficulty with Fresnel's aether hypothesis arose from the juxtaposition of the two well-established theories of Newtonian dynamics and Maxwell's electromagnetism. Under a Galilean transformation the equations of Newtonian dynamics are invariant, whereas those of electromagnetism are not. Basically this means that while physics should remain the same in non-accelerated experiments, light would not follow the same rules because it is travelling in the universal "aether frame". Some effect caused by this difference should be detectable.

A simple example concerns the model on which aether was originally built: sound. The speed of propagation for mechanical waves, the speed of sound, is defined by the mechanical properties of the medium. Sound travels 4.3 times faster in water than in air. This explains why a person hearing an explosion underwater and quickly surfacing can hear it again as the slower travelling sound arrives through the air. Similarly, a traveller on an airliner can still carry on a conversation with another traveller because the sound of words is travelling along with the air inside the aircraft. This effect is basic to all Newtonian dynamics, which says that everything from sound to the trajectory of a thrown baseball should all remain the same in the aircraft flying (at least at a constant speed) as if still sitting on the ground. This is the basis of the Galilean transformation, and the concept of frame of reference.

But the same was not supposed to be true for light, since Maxwell's mathematics demanded a single universal speed for the propagation of light, based, not on local conditions, but on two measured

properties, the permittivity and permeability of free space, that were assumed to be the same throughout the universe. If these numbers did change, there should be noticeable effects in the sky; stars in different directions would have different colours, for instance.

Thus at any point there should be one special coordinate system, "at rest relative to the aether". Maxwell noted in the late 1870s that detecting motion relative to this aether should be easy enough—light travelling along with the motion of the Earth would have a different speed than light travelling backward, as they would both be moving against the unmoving aether. Even if the aether had an overall universal flow, changes in position during the day/night cycle, or over the span of seasons, should allow the drift to be detected.

First order experiments

Although the aether is almost stationary according to Fresnel, his theory predicts a positive outcome of aether drift experiments only to *second* order in v/c , because Fresnel's dragging coefficient would cause a negative outcome of all optical experiments capable of measuring effects to *first* order in v/c . This was confirmed by the following first-order experiments, which all gave negative results. The following list is based on the description of Wilhelm Wien (1898), with changes and additional experiments according to the descriptions of Edmund Taylor Whittaker (1910) and Jakob Laub (1910):^{[4][16][17]}

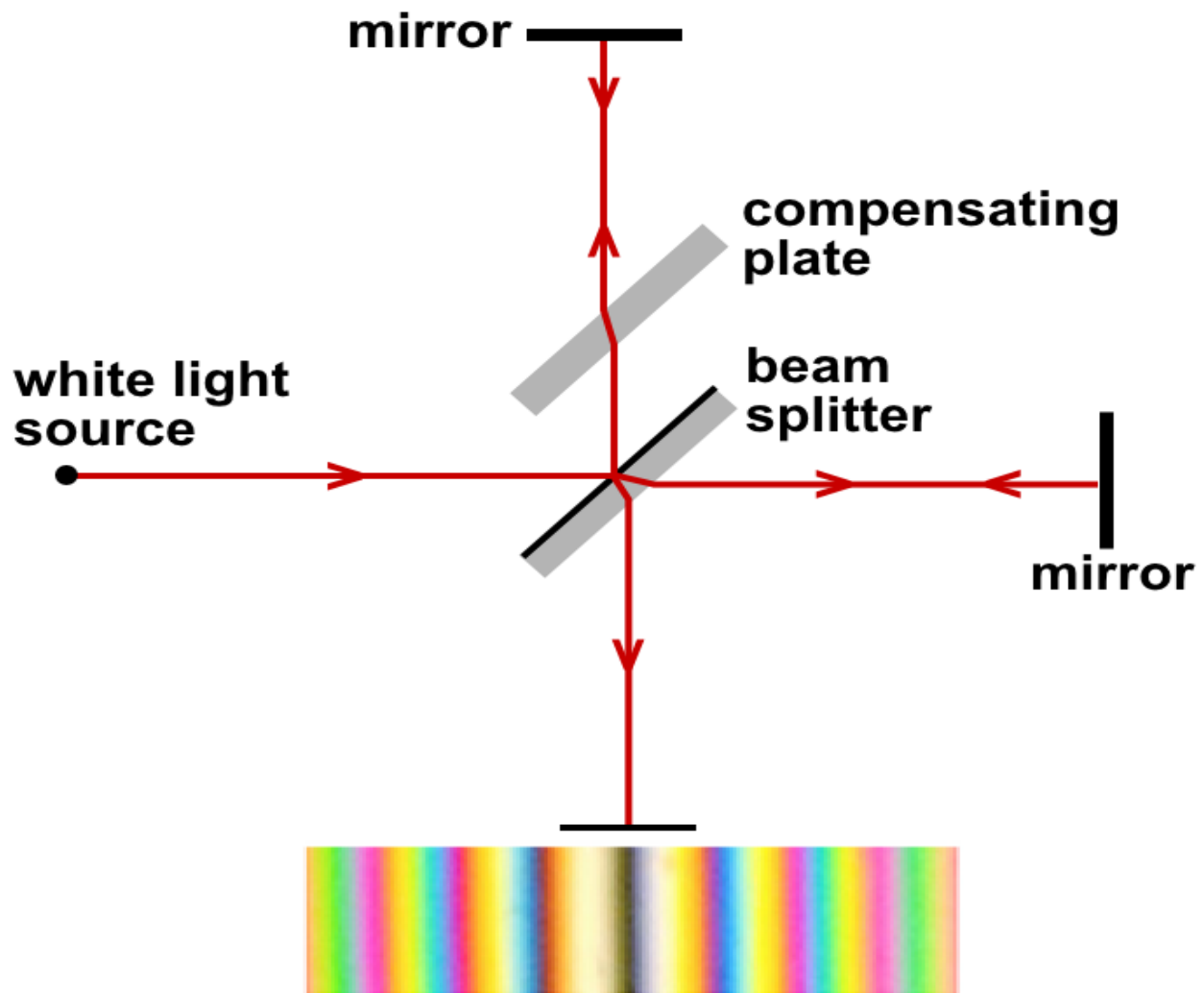
- The experiment of [François Arago](#) (1810), to confirm whether refraction, and thus the aberration of light, is influenced by Earth's motion. Similar experiments were conducted by George Biddell Airy (1871) by means of a telescope filled with water, and Éleuthère Mascart (1872).^{[18][19][20]}
- The experiment of Fizeau (1860), to find whether the rotation of the polarization plane through glass columns is changed by Earth's motion. He obtained a positive result, but Lorentz could show that the results have been contradictory. DeWitt Bristol Brace (1905) and Strasser (1907) repeated the experiment with improved accuracy, and obtained negative results.^{[21][22][23]}
- The experiment of Martin Hoek (1868). This experiment is a more precise variation of the Fizeau experiment (1851). Two light rays were sent in opposite directions – one of them traverses a path filled with resting water, the other one follows a path through air. In agreement with Fresnel's dragging coefficient, he obtained a negative result.^[24]
- The experiment of Wilhelm Klinkerfues (1870) investigated whether an influence of Earth's motion on the absorption line of [sodium](#) exists. He obtained a positive result, but this was shown to be an experimental error, because a repetition of the experiment by Haga (1901) gave a negative result.^{[25][26]}
- The experiment of Ketteler (1872), in which two rays of an interferometer were sent in opposite directions through two mutually inclined tubes filled with water. No change of the interference fringes occurred. Later, Mascart (1872) showed that the interference fringes of polarized light in calcite remained uninfluenced as well.^{[27][28]}
- The experiment of Éleuthère Mascart (1872) to find a change of rotation of the polarization plane in quartz. No change of rotation was found when the light rays had the direction of Earth's motion and then the opposite direction. Lord Rayleigh conducted similar experiments with improved accuracy, and obtained a negative result as well.^{[20][28][29]}

Besides those optical experiments, also electrodynamic first-order experiments were conducted, which should have led to positive results according to Fresnel. However, Hendrik Antoon Lorentz (1895) modified Fresnel's theory and showed that those experiments can be explained by a stationary aether as well:^[30]

- The experiment of Wilhelm Röntgen (1888), to find whether a charged condenser produces magnetic forces due to Earth's motion.^[31]

- The experiment of Theodor des Coudres (1889), to find whether the inductive effect of two wire rolls upon a third one is influenced by the direction of Earth's motion. Lorentz showed that this effect is cancelled to first order by the electrostatic charge (produced by Earth's motion) upon the conductors.^[32]
- The experiment of Königsberger (1905). The plates of a condenser are located in the field of a strong electromagnet. Due to Earth's motion, the plates should have become charged. No such effect was observed.^[33]
- The experiment of Frederick Thomas Trouton (1902). A condenser was brought parallel to Earth's motion, and it was assumed that momentum is produced when the condenser is charged. The negative result can be explained by Lorentz's theory, according to which the electromagnetic momentum compensates the momentum due to Earth's motion. Lorentz could also show, that the sensitivity of the apparatus was much too low to observe such an effect.^[34]

Second order experiments



The Michelson–Morley experiment compared the time for light to reflect from mirrors in two orthogonal directions. <https://handwiki.org/wiki/index.php?curid=1079321>

While the *first-order* experiments could be explained by a modified stationary aether, more precise *second-order* experiments were expected to give positive results, however, no such results could be found.

The famous Michelson–Morley experiment compared the source light with itself after being sent in different directions, looking for changes in phase in a manner that could be measured with extremely high accuracy. In this experiment, their goal was to determine the velocity of the Earth through the aether.^{[35][36]} The publication of their result in 1887, the null result, was the first clear demonstration that something was seriously wrong with the aether hypothesis (Michelson's first experiment in 1881 was not entirely conclusive). In this case the MM experiment yielded a shift of the fringing pattern of about 0.01 of a fringe, corresponding to a small velocity. However, it was incompatible with the expected aether wind effect due to the Earth's (seasonally varying) velocity which would have required a shift of 0.4 of a fringe, and the error was small enough that the value may have indeed been zero. Therefore, the null hypothesis, the hypothesis that there was no aether wind, could not be rejected. More modern experiments have since reduced the possible value to a number very close to zero, about 10^{-17} .

It is obvious from what has gone before that it would be hopeless to attempt to solve the question of the motion of the solar system by observations of optical phenomena at the surface of the earth.

—A. Michelson and E. Morley. "On the Relative Motion of the Earth and the Luminiferous Æther". *Phil. Mag. S. 5*. Vol. 24. No. 151. Dec. 1887.^[37]

A series of experiments using similar but increasingly sophisticated apparatuses all returned the null result as well. Conceptually different experiments that also attempted to detect the motion of the aether were the Trouton–Noble experiment (1903),^[38] whose objective was to detect torsion effects caused by electrostatic fields, and the experiments of Rayleigh and Brace (1902, 1904),^{[39][40]} to detect double refraction in various media. However, all of them obtained a null result, like Michelson–Morley (MM) previously did.

These "aether-wind" experiments led to a flurry of efforts to "save" aether by assigning to it ever more complex properties, while only few scientists, like Emil Cohn or Alfred Bucherer, considered the possibility of the abandonment of the aether hypothesis. Of particular interest was the possibility of "aether entrainment" or "aether drag", which would lower the [magnitude](#) of the measurement, perhaps enough to explain the results of the Michelson–Morley experiment. However, as noted earlier, aether dragging already had problems of its own, notably aberration. In addition, the interference experiments of Lodge (1893, 1897) and Ludwig Zehnder (1895), aimed to show whether the aether is dragged by various, rotating masses, showed no aether drag.^{[41][42][43]} A more precise measurement was made in the Hammar experiment (1935), which ran a complete MM experiment with one of the "legs" placed between two massive lead blocks.^[44] If the aether was dragged by mass then this experiment would have been able to detect the drag caused by the lead, but again the null result was achieved. The theory was again modified, this time to suggest that the entrainment only worked for very large masses or those masses with large magnetic fields. This too was shown to be incorrect by the Michelson–Gale–Pearson experiment, which detected the Sagnac effect due to Earth's rotation (see Aether drag hypothesis).

Another, completely different attempt to save "absolute" aether was made in the Lorentz–FitzGerald contraction hypothesis, which posited that *everything* was affected by travel through the aether. In this theory the reason the Michelson–Morley experiment "failed" was that the apparatus contracted in length in the direction of travel. That is, the light was being affected in the "natural" manner by its travel through the aether as predicted, but so was the apparatus itself, cancelling out any difference when measured. FitzGerald had inferred this hypothesis from a paper by Oliver Heaviside. Without referral to an aether, this physical interpretation of relativistic effects was shared by Kennedy and Thorndike in 1932 as they

concluded that the interferometer's arm contracts and also the frequency of its light source "very nearly" varies in the way required by relativity.^{[45][46]}

Similarly the Sagnac effect, observed by G. Sagnac in 1913, was immediately seen to be fully consistent with special relativity.^{[47][48]} In fact, the Michelson-Gale-Pearson experiment in 1925 was proposed specifically as a test to confirm the relativity theory, although it was also recognized that such tests, which merely measure absolute rotation, are also consistent with non-relativistic theories.^[49]

During the 1920s, the experiments pioneered by Michelson were repeated by Dayton Miller, who publicly proclaimed positive results on several occasions, although they were not large enough to be consistent with any known aether theory. However, other researchers were unable to duplicate Miller's claimed results. Over the years the experimental accuracy of such measurements has been raised by many orders of magnitude, and no trace of any violations of Lorentz invariance has been seen. (A later re-analysis of Miller's results concluded that he had underestimated the variations due to temperature.)

Since the Miller experiment and its unclear results there have been many more experimental attempts to detect the aether. Many experimenters have claimed positive results. These results have not gained much attention from mainstream science, since they contradict a large quantity of high-precision measurements, all the results of which were consistent with special relativity.^[50]

3. Lorentz Aether Theory

Between 1892 and 1904, Hendrik Lorentz developed an electron-aether theory, in which he introduced a strict separation between matter (electrons) and aether. In his model the aether is completely motionless, and won't be set in motion in the neighborhood of ponderable matter. Contrary to earlier electron models, the electromagnetic field of the aether appears as a mediator between the electrons, and changes in this field cannot propagate faster than the speed of light. A fundamental concept of Lorentz's theory in 1895 was the "theorem of corresponding states" for terms of order v/c .^[30] This theorem states that an observer moving relative to the aether makes the same observations as a resting observer, after a suitable change of variables. Lorentz noticed that it was necessary to change the space-time variables when changing frames and introduced concepts like physical length contraction (1892)^[51] to explain the Michelson-Morley experiment, and the mathematical concept of local time (1895) to explain the aberration of light and the Fizeau experiment. This resulted in the formulation of the so-called Lorentz transformation by [Joseph Larmor](#) (1897, 1900)^{[52][53]} and Lorentz (1899, 1904),^{[54][55]} whereby (it was noted by Larmor) the complete formulation of local time is accompanied by some sort of time dilation of electrons moving in the aether. As Lorentz later noted (1921, 1928), he considered the time indicated by clocks resting in the aether as "true" time, while local time was seen by him as a heuristic working hypothesis and a mathematical artifice.^{[56][57]} Therefore, Lorentz's theorem is seen by modern authors as being a mathematical transformation from a "real" system resting in the aether into a "fictitious" system in motion.^{[6][58][59]}

The work of Lorentz was mathematically perfected by Henri Poincaré, who formulated on many occasions the Principle of Relativity and tried to harmonize it with electrodynamics. He declared simultaneity only a convenient convention which depends on the speed of light, whereby the constancy of the speed of light would be a useful postulate for making the laws of nature as simple as possible. In 1900 and 1904^{[60][61]} he physically interpreted Lorentz's local time as the result of clock synchronization by light signals. In June and July 1905^{[62][63]} he declared the relativity principle a general law of nature, including [gravitation](#). He corrected some mistakes of Lorentz and proved the Lorentz covariance of the electromagnetic equations. However, he used the notion of an aether as a perfectly undetectable medium and distinguished between apparent and real time, so most historians of science argue that he failed to invent special relativity.^{[6][58][64]}

4. End of Aether

4.1. Special Relativity

Aether theory was dealt another blow when the Galilean transformation and Newtonian dynamics were both modified by Albert Einstein's special theory of relativity, giving the mathematics of Lorentzian electrodynamics a new, "non-aether" context.^[65] Unlike most major shifts in scientific thought, special relativity was adopted by the scientific community remarkably quickly, consistent with Einstein's later comment that the laws of physics described by the Special Theory were "ripe for discovery" in 1905.^[66] Max Planck's early advocacy of the special theory, along with the elegant formulation given to it by Hermann Minkowski, contributed much to the rapid acceptance of special relativity among working scientists.

Einstein based his theory on Lorentz's earlier work. Instead of suggesting that the mechanical properties of objects changed with their constant-velocity motion through an undetectable aether, Einstein proposed to deduce the characteristics that any successful theory must possess in order to be consistent with the most basic and firmly established principles, independent of the existence of a hypothetical aether. He found that the Lorentz transformation must transcend its connection with Maxwell's equations, and must represent the fundamental relations between the space and time coordinates of inertial frames of reference. In this way he demonstrated that the laws of physics remained invariant as they had with the Galilean transformation, but that light was now invariant as well.

With the development of the special theory of relativity, the need to account for a single universal frame of reference had disappeared – and acceptance of the 19th-century theory of a luminiferous aether disappeared with it. For Einstein, the Lorentz transformation implied a [conceptual change](#): that the concept of position in space or time was not absolute, but could differ depending on the observer's location and velocity.

Moreover, in another paper published the same month in 1905, Einstein made several observations on a then-thorny problem, the photoelectric effect. In this work he demonstrated that light can be considered as particles that have a "wave-like nature". Particles obviously do not need a medium to travel, and thus, neither did light. This was the first step that would lead to the full development of quantum mechanics, in which the wave-like nature *and* the particle-like nature of light are both considered as valid descriptions of light. A summary of Einstein's thinking about the aether hypothesis, relativity and light quanta may be found in his 1909 (originally German) lecture "The Development of Our Views on the Composition and Essence of Radiation".^[67]

Lorentz on his side continued to use the aether hypothesis. In his lectures of around 1911, he pointed out that what "the theory of relativity has to say ... can be carried out independently of what one thinks of the aether and the time". He commented that "whether there is an aether or not, electromagnetic fields certainly exist, and so also does the energy of the electrical oscillations" so that, "if we do not like the name of 'aether', we must use another word as a peg to hang all these things upon". He concluded that "one cannot deny the bearer of these concepts a certain substantiality".^{[58][68]}

4.2. Other models

In later years there have been a few individuals who advocated a neo-Lorentzian approach to physics, which is Lorentzian in the sense of positing an absolute true state of rest that is undetectable and which plays no role in the predictions of the theory. (No violations of Lorentz covariance have ever been detected, despite strenuous efforts.) Hence these theories resemble the 19th century aether theories in

name only. For example, the founder of quantum field theory, Paul Dirac, stated in 1951 in an article in *Nature*, titled "Is there an Aether?" that "we are rather forced to have an aether".^{[69][70]} However, Dirac never formulated a complete theory, and so his speculations found no acceptance by the scientific community.

4.3. Einstein's Views on the Aether

When Einstein was still a student in the Zurich Polytechnic in 1900, he was very interested in the idea of aether. His initial proposal of research thesis was to do an experiment to measure how fast the Earth was moving through the aether.^[71] "The velocity of a wave is proportional to the square root of the elastic forces which cause [its] propagation, and inversely proportional to the mass of the aether moved by these forces."^[72]

In 1916, after Einstein completed his foundational work on general relativity, Lorentz wrote a letter to him in which he speculated that within general relativity the aether was re-introduced. In his response Einstein wrote that one can actually speak about a "new aether", but one may not speak of motion in relation to that aether. This was further elaborated by Einstein in some semi-popular articles (1918, 1920, 1924, 1930).^{[73][74][75][76][77][78][79]}

In 1918 Einstein publicly alluded to that new definition for the first time.^[73] Then, in the early 1920s, in a lecture which he was invited to give at Lorentz's university in Leiden, Einstein sought to reconcile the theory of relativity with Lorentzian aether. In this lecture Einstein stressed that special relativity took away the last mechanical property of the aether: immobility. However, he continued that special relativity does not necessarily rule out the aether, because the latter can be used to give physical reality to acceleration and rotation. This concept was fully elaborated within general relativity, in which physical properties (which are partially determined by matter) are attributed to space, but no substance or state of motion can be attributed to that "aether" (by which he meant curved space-time).^{[74][79][80]}

In another paper of 1924, named "Concerning the Aether", Einstein argued that Newton's absolute space, in which acceleration is absolute, is the "Aether of Mechanics". And within the electromagnetic theory of Maxwell and Lorentz one can speak of the "Aether of Electrodynamics", in which the aether possesses an absolute state of motion. As regards special relativity, also in this theory acceleration is absolute as in Newton's mechanics. However, the difference from the electromagnetic aether of Maxwell and Lorentz lies in the fact, that "because it was no longer possible to speak, in any absolute sense, of simultaneous states at different locations in the aether, the aether became, as it were, four-dimensional since there was no objective way of ordering its states by time alone". Now the "aether of special relativity" is still "absolute", because matter is affected by the properties of the aether, but the aether is not affected by the presence of matter. This asymmetry was solved within general relativity. Einstein explained that the "aether of general relativity" is not absolute, because matter is influenced by the aether, just as matter influences the structure of the aether.^[75]

The only similarity of this relativistic aether concept with the classical aether models lies in the presence of physical properties in space, which can be identified through geodesics. As historians such as John Stachel argue, Einstein's views on the "new aether" are not in conflict with his abandonment of the aether in 1905. As Einstein himself pointed out, no "substance" and no state of motion can be attributed to that new aether. Einstein's use of the word "aether" found little support in the scientific community, and played no role in the continuing development of modern physics.^{[77][78][79]}

5. Aether Concepts

- Aether theories
- Aether (classical element)
- [Aether drag hypothesis](#)

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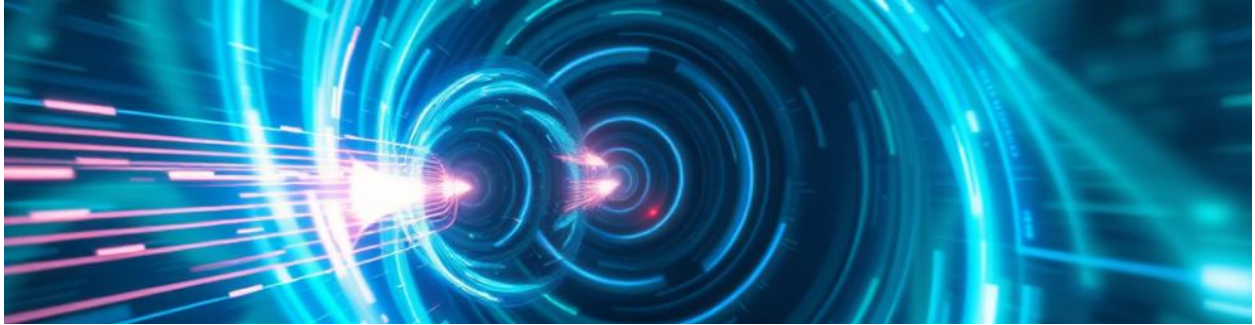
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ANTI-GRAVITY PROPULSION

Judging from patents filed [1](#) [2](#) [3](#), academic studies published [4](#) [5](#) and public UAP committees being instituted in some of the most developed countries [6](#) [7](#), it can be estimated that within the next decade a major announcement is going to be made regarding existence and development of anti-gravity propulsion. Probability of disclosure is higher in the event of a hot war, either on US soil alone or as a global WW3-style conflict. The physical theory underlying such a propulsion seems to be based on hydro-magneto-dynamic effects of heavy ion plasma related to magnetic monopoles, 4th spatial dimension and natural extension of Maxwell's equations to include gravity as the 3rd force in electro-gravito-magnetic interactions.

Basically you resonate the charged ions in plasma in such a way as if they were a spring with a negative spring constant and since the charges are coupled to the underlying medium of space-time, this results in an inertial force that is opposite to gravitational force.

It seems that this process is able to access zero-point/negative energy of the vacuum but of course there's a lot more nuance to that. What can be most surprising to some, there are at least a few extremely simple experiments that can shed more light on the matter and in some cases definitely prove that those phenomena are real. [8](#)

Be mindful that current academic knowledge on the subject is theoretical at best and often any mention of those topics will get one laughed out of academia, while the engineers and physicist working for the military won't say a thing – for obvious reasons.

One notable exception is United States Space Force engineer Salvatore Pais [9](#), whose patents got mentioned in the first paragraph. He is rather outspoken about the underlying physics and an key effect describing

mechanism of action named after him i.e. the Pais Effect, which is in his own words a “controlled motion of electrically-charged matter from solids to plasma states subjected to accelerated vibration and/or accelerated spin via rapid acceleration transients.”

Anyways, I’d be much surprised if most armies of serious countries weren’t:

1. aware of that technology, especially after the disappearance of flight MH370^{10 11}
2. developing this technology as we speak.

Countries without at least a proof of concept, should then not be viewed as real contenders for dominion over the new post-war world.

PS. This topic is much more complex than indicated in this short article – with multiple layers of narratives, themes and factions of various allegiances. Any detailed analysis is well outside the scope of this blog.

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Beyond Conventional Physics: Extended Electrodynamics, Lattice Confinement Fusion, Zero-Point Energy & Advanced Propulsion

Seems like the “within the next decade” timeframe I was referring to in [my previous entry](#) is going to be much sooner than expected.

Below is a [podcast interview](#) with top executives and engineers from US government and private sector discussing advanced physics research.

69. Beyond Conventional Physics: Extended Electrodynamics, Lattice Confinement Fusion, Zero-Point Energy & Advanced Propulsion

They talk about quantum technology, vector scalar potencial, extended electrodynamics etc. To an amateur and/or untrained observer those words don't mean much, but those are all codewords for gravity, cold fusion and full set of Maxwell's equations that were censored by Oliver Heavyside to hide gravity from the public.

Please note that gravitational interactions are 40 orders of magnitude weaker than electrostatic interactions, so in any day to day experiences with magnets and electric current we just don't notice the miniscule gravitational component. In fact even scientific studies aren't able to easily discern its effects from the lab results if the scientists aren't carefully looking for them – and they aren't because anti-gravity and aether has been made into a joke.

This podcast is a glaring proof that the gravitational research and almost limitless energy from the vacuum is a fact that has been known to the select few for almost a century now.

Since no guest on any morning TV show hasn't came forward and spelled out for the general public that, yes, antigravity is possible and cold fusion is an effective working power source, so most people still won't believe that it is so. Especially since it means that most hardship, deaths and wars for resources were avoidable, if only that research had not been censored and hidden from the public, instead of being responsibly let out for the human kind to use.

All the recent UFO/UAP “drama” is only accelerating the disclosure, so the people can finally listen to serious people talking about advanced physics. However for them to be perceived serious they can't use the terms that had been so purposefully and thoroughly discredited in the past.

Make no mistake about it. Cold fusion is real, anti-gravity propulsion is real and extended electrodynamics is only “extended” now, because it has been neutered in the past.

Unfortunately, IMHO this technology is first going to be used for war, before it's going to be used for peace – as usual.

References:

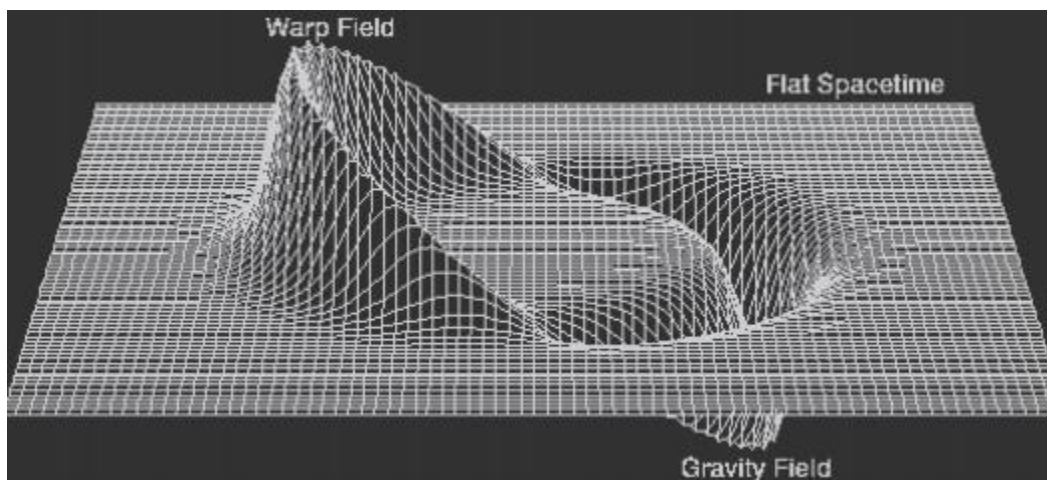
Main image is from a research paper “*The Quantum Field Of A Magnet Shown By A Nanomagnetic Ferrolens*”: https://www.researchgate.net/publication/326256770_The_Quantum_Field_Of_A_Magnet_Shown_By_A_Nanomagnetic_Ferrolens#fullTextFileContent – definitely worth a read.

Space-Time Metric Engineering

The use of metric engineering to **manipulate the structure of space and time**. Manipulation and fine control of space-time allows the creation of artificial wormholes, reactionless drives, and artificial universes.

Spacetime Metric Engineering

A theme that has come to the fore in advanced planning for long-range space exploration is the concept that empty space itself (the quantum vacuum, or spacetime metric) might be engineered so as to provide energy/thrust for future space vehicles. Although far-reaching, such a proposal is solidly grounded in modern physical theory, and therefore the possibility that matter/ vacuum interactions might be engineered for space-flight applications is not a priori ruled out. As examples, the current development of theoretical physics addresses such topics as warp drives, traversable wormholes and time machines that provide for such vacuum engineering possibilities. Our work provides a broad perspective of the physics and correlates/consequences of the engineering of the spacetime metric.



Alcubierre warp drive metric

The use of metric engineering to manipulate the structure of space and time. Manipulation and fine control of space-time allows the creation of artificial wormholes, reactionless drives, and artificial universes. However almost all forms of space-time engineering can only be successfully performed by ArticlePDF Available

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References:

Main image is from a research paper “*The Quantum Field Of A Magnet Shown By A Nanomagnetic*

Ferrolens”: https://www.researchgate.net/publication/326256770_The_Quantum_Field_Of_A_Magnet_Shown_By_A_Nanomagnetic_Ferrolens#fullTextFileContent – definitely worth a read.

You need to curve space- time itself to tap into the aether...

Geodesic Time-like Curves

Geodesics in general relativity

In [general relativity](#), a **geodesic** generalizes the notion of a "straight line" to curved [spacetime](#). Importantly, the [world line](#) of a particle free from all external, non-gravitational forces is a particular type of geodesic. In other words, a freely moving or falling particle always moves along a geodesic.

In general relativity, gravity can be regarded as not a force but a consequence of a [curved spacetime](#) geometry where the source of curvature is the [stress–energy tensor](#) (representing matter, for instance). Thus, for example, the path of a planet orbiting a star is the projection of a geodesic of the curved four-dimensional (4-D) spacetime geometry around the star onto three-dimensional (3-D) space.

Mathematical expression

[\[edit\]](#)

The full **geodesic equation** is $\frac{d^2 x^\mu}{ds^2} + \Gamma^\mu_{\alpha\beta} \frac{dx^\alpha}{ds} \frac{dx^\beta}{ds} = 0$ where s is a scalar parameter of motion (e.g.

the [proper time](#)), and $\Gamma^\mu_{\alpha\beta}$ are [Christoffel symbols](#) (sometimes called the [affine connection](#) coefficients or [Levi-Civita connection](#) coefficients) symmetric in the two lower indices. Greek indices may take the values: 0, 1, 2, 3 and the [summation](#)

[convention](#) is used for repeated indices $\Gamma^\mu_{\alpha\beta}$ and $\frac{dx^\alpha}{ds}$. The quantity on the left-hand-side of this equation is the acceleration of a particle, so this equation is analogous to [Newton's laws of motion](#), which likewise provide formulae for the acceleration of a

particle. The Christoffel symbols are functions of the four spacetime coordinates and so are independent of the velocity or acceleration or other characteristics of a [test particle](#) whose motion is described by the geodesic equation.

Equivalent mathematical expression using coordinate time as parameter

[\[edit\]](#)

So far the geodesic equation of motion has been written in terms of a scalar

parameter s . It can alternatively be written in terms of the time coordinate, (here we have used the [triple bar](#) to signify a definition). The geodesic equation of motion then

becomes:

This formulation of the geodesic equation of motion can be useful for computer calculations and to compare General Relativity with Newtonian Gravity.^[1] It is straightforward to derive this form of the geodesic equation of motion from the form which uses proper time as a parameter using the [chain rule](#). Notice that both sides of this last equation vanish when the μ index is set to zero. If the particle's velocity is

small enough, then the geodesic equation reduces to this:

Here the Latin index n takes the values [1,2,3]. This equation simply means that all test particles at a particular place and time will have the same acceleration, which is a well-known feature of Newtonian gravity. For example, everything floating around in the [International Space Station](#) will undergo roughly the same acceleration due to gravity.

Derivation directly from the equivalence principle

[\[edit\]](#)

Physicist [Steven Weinberg](#) has presented a derivation of the geodesic equation of motion directly from the [equivalence principle](#).^[2] The first step in such a derivation is to suppose that a free falling particle does not accelerate in the neighborhood of a [point-](#)

[event](#) with respect to a freely falling coordinate system (). Setting , we have the

following equation that is locally applicable in free fall: The next step is to employ

the multi-dimensional chain rule. We have: Differentiating once more with respect to

the time, we have: We have already said that the left-hand-side of this last equation

must vanish because of the Equivalence Principle. Therefore: Multiply both sides of

this last equation by the following quantity: Consequently, we have this:

Weinberg defines the affine connection as follows:^[3] which leads to this formula:

Notice that, if we had used the proper time “s” as the parameter of motion, instead of using the locally inertial time coordinate “T”, then our derivation of the geodesic equation of motion would be complete. In any event, let us continue by applying the

one-dimensional [chain rule](#):

As before, we can set $\lambda = t$. Then the first derivative of x^α with respect to t is one and the second derivative is zero. Replacing λ with zero gives:

Subtracting dx^α/dt times this from the previous equation gives: $\frac{d^2x^\alpha}{dt^2} + \Gamma^\alpha_{\beta\gamma} \frac{dx^\beta}{dt} \frac{dx^\gamma}{dt} = 0$ which is a form of the geodesic equation of motion (using the coordinate time as parameter).

The geodesic equation of motion can alternatively be derived using the concept of [parallel transport](#).^[4]

Deriving the geodesic equation via an action

[\[edit\]](#)

We can (and this is the most common technique) derive the geodesic equation via the [action](#) principle. Consider the case of trying to find a geodesic between two timelike-separated events.

Let the action be $S = -mc \int \sqrt{-g_{\mu\nu} dx^\mu dx^\nu}$ where $ds = \sqrt{-g_{\mu\nu} dx^\mu dx^\nu}$ is the [line element](#). There is a negative sign inside the square root because the curve must be timelike. To get the geodesic equation we must vary this action. To do this let us parameterize this action with respect to a

parameter λ . Doing this we get:

We can now go ahead and vary this action with respect to the curve $x^\mu(\lambda)$. By

the [principle of least action](#) we get:

Using the product rule we get: $\frac{d}{d\lambda} \left(\frac{dx^\mu}{d\lambda} \frac{\delta S}{\delta \dot{x}^\mu} \right) - \frac{\delta S}{\delta x^\mu} = 0$ where

Integrating by-parts the last term and dropping the total derivative (which equals to zero

at the boundaries) we get that:

Simplifying a bit we see that: $\frac{d}{d\lambda} \left(\frac{dx^\mu}{d\lambda} \frac{\delta S}{\delta \dot{x}^\mu} \right) = 0$ so, multiplying this equation by $\frac{d\lambda}{d\lambda}$ we get:

So by [Hamilton's principle](#) we find that the [Euler–Lagrange equation](#) is

Multiplying by the inverse [metric tensor](#) $g^{\mu\nu}$ we get that

Thus we get the geodesic equation: $\frac{d^2x^\mu}{d\lambda^2} + \Gamma^\mu_{\alpha\beta} \frac{dx^\alpha}{d\lambda} \frac{dx^\beta}{d\lambda} = 0$ with the [Christoffel symbol](#) defined in terms of the metric tensor as

(Note: Similar derivations, with minor amendments, can be used to produce analogous results for geodesics between light-like^[citation needed] or space-like separated pairs of points.)

Equation of motion may follow from the field equations for empty space

[\[edit\]](#)

[Albert Einstein](#) believed that the geodesic equation of motion can be derived from the [field equations for empty space](#), i.e. from the fact that the [Ricci curvature](#) vanishes. He wrote:^[5]

It has been shown that this law of motion — generalized to the case of arbitrarily large gravitating masses — can be derived from the field equations of empty space alone. According to this derivation the law of motion is implied by the condition that the field be singular nowhere outside its generating mass points.

and ^[6]

One of the imperfections of the original relativistic theory of gravitation was that as a field theory it was not complete; it introduced the independent postulate that the law of motion of a particle is given by the equation of the geodesic.

A complete field theory knows only fields and not the concepts of particle and motion. For these must not exist independently from the field but are to be treated as part of it.

On the basis of the description of a particle without singularity, one has the possibility of a logically more satisfactory treatment of the combined problem: The problem of the field and that of the motion coincide.

Both physicists and philosophers have often repeated the assertion that the geodesic equation can be obtained from the field equations to describe the motion of a [gravitational singularity](#), but this claim remains disputed.^[7] According to [David Malament](#), “Though the geodesic principle can be recovered as theorem in general relativity, it is not a consequence of Einstein’s equation (or the conservation principle) alone. Other assumptions are needed to derive the theorems in question.”^[8] Less controversial is the notion that the field equations determine the motion of a fluid or dust, as distinguished from the motion of a point-singularity.^[9]

Extension to the case of a charged particle

[\[edit\]](#)

In deriving the geodesic equation from the equivalence principle, it was assumed that particles in a local inertial coordinate system are not accelerating. However, in real life, the particles may be charged, and therefore may be accelerating locally in accordance

with the [Lorentz force](#). That is: with

The [Minkowski tensor](#) is given by:

These last three equations can be used as the starting point for the derivation of an equation of motion in General Relativity, instead of assuming that acceleration is zero in free fall.^[2] Because the Minkowski tensor is involved here, it becomes necessary to introduce something called the [metric tensor](#) in General Relativity. The metric tensor g is symmetric, and locally reduces to the Minkowski tensor in free fall. The

resulting equation of motion is as follows:^[10] with

This last equation signifies that the particle is moving along a timelike geodesic; massless particles like the [photon](#) instead follow null geodesics (replace -1 with zero on the right-hand side of the last equation). It is important that the last two equations are consistent with each other, when the latter is differentiated with respect to proper time,

and the following formula for the Christoffel symbols ensures that consistency: This last equation does not involve the electromagnetic fields, and it is applicable even in the limit as the electromagnetic fields vanish. The letter g with superscripts refers to the [inverse](#) of the metric tensor. In General Relativity, indices of tensors are lowered and raised by [contraction](#) with the metric tensor or its inverse, respectively.

Geodesics as curves of stationary interval

[\[edit\]](#)

A geodesic between two events can also be described as the curve joining those two events which has a stationary [interval](#) (4-dimensional "length"). *Stationary* here is used in the sense in which that term is used in the [calculus of variations](#), namely, that the interval along the curve varies minimally among curves that are nearby to the geodesic.

In Minkowski space there is only one geodesic that connects any given pair of events, and for a time-like geodesic, this is the curve with the longest [proper time](#) between the two events. In curved spacetime, it is possible for a pair of widely separated events to have more than one time-like geodesic between them. In such instances, the proper times along several geodesics will not in general be the same. For some geodesics in such instances, it is possible for a curve that connects the two events and is nearby to the geodesic to have either a longer or a shorter proper time than the geodesic.^[11]

For a space-like geodesic through two events, there are always nearby curves which go through the two events that have either a longer or a shorter [proper length](#) than the geodesic, even in Minkowski space. In Minkowski space, the geodesic will be a straight line. Any curve that differs from the geodesic purely spatially (*i.e.* does not change the time coordinate) in any inertial frame of reference will have a longer proper length than the geodesic, but a curve that differs from the geodesic purely temporally (*i.e.* does not change the space coordinates) in such a frame of reference will have a shorter proper length.

The interval of a curve in spacetime is

Then, the [Euler–Lagrange equation](#), becomes, after some calculation,

where

show

Proof

If the parameter s is chosen to be affine, then the right side of the above equation

vanishes (because $\frac{ds}{ds}$ is constant). Finally, we have the geodesic equation

Derivation using autoparallel transport

[\[edit\]](#)

The geodesic equation can be alternatively derived from the autoparallel transport of curves. The derivation is based on the lectures given by Frederic P. Schuller at the We-Heraeus International Winter School on Gravity & Light.

Let M be a smooth manifold with connection and γ be a curve on the manifold.

The curve is said to be autoparallely transported if and only if $\nabla_{\dot{\gamma}} \dot{\gamma} = 0$.

In order to derive the geodesic equation, we have to choose a chart (U, φ) : Using the linearity and the Leibniz rule:

Using how the connection acts on functions ($\nabla_X f = X(f)$) and expanding the second term with the help of the connection coefficient functions:

The first term can be simplified to $\ddot{\gamma}^i$. Renaming the dummy indices:

We finally arrive to the geodesic equation:

Charged Parity Inversion in the Quantum Vacuum

Exploring the Intrigues of Parity Violation and Quantum Anomalies

In the realms of physics, particularly quantum mechanics and field theory, certain principles challenge our classical understandings of symmetry in nature. One striking phenomenon known as **parity violation** alongside concepts like **quantum anomalies** and **CP symmetry** unveils some of the subtleties inherent in the quantum world. This article will delve into these complex ideas, breaking them down into understandable segments while connecting to their implications in Quantum Field Theory (QFT).

Understanding Parity Violation

Parity, in physics, refers to the symmetry of physical processes under spatial inversion—that is, flipping the system into a mirror image of itself. Classical physics suggested that the laws of physics were invariant under such transformations, meaning that the physical phenomena should behave the same way even if the spatial coordinates are inverted. This assumption holds true in electrostatics, gravity, and much of classical mechanics. However, the discovery of parity violation in the 1950s showed that this principle does not universally apply, particularly in the realm of weak nuclear interactions (one of the four fundamental forces in nature).

The landmark experiment by Chien-Shiung Wu in 1957 involving beta decay of cobalt-60 atoms demonstrated that the weak force does not comply with parity conservation. During this decay, electrons were observed to preferentially emit in a direction that was related to the nuclear spin, a clear counterexample to parity invariance. This discovery was foundational, signaling that not all interactions respect mirror symmetry, and earned its discoverers, Tsung-Dao Lee and Chen Ning Yang, the Nobel Prize in physics.

Quantum Anomalies: Breaking Classical Symmetry

Quantum anomalies occur when a symmetry present in a classical theory does not survive the transition to a quantum theory. These are often encountered in quantum field theories where the operations used to regularize and renormalize the theories lead to the unexpected breaking of symmetries. A common example arises in the form of chiral anomalies, where symmetries involving 'handedness' of particle interactions do not hold in a quantum context, despite being valid in a classical approach.

These breakdowns are not just theoretical curiosities; they have practical implications, notably in the standard model of particle physics which describes the fundamental particles and their interactions. Anomalies must be carefully managed to preserve the consistency and predictability of the model.

CP Symmetry and Its Violations

Charge Parity (CP) symmetry combines the inversion of spatial coordinates (parity, P) with the swapping of particles with their corresponding antiparticles (charge conjugation, C). In terms of physical laws, CP symmetry suggests that the laws should be the same if a particle is replaced by its antiparticle and its spatial coordinates are simultaneously inverted. Originally, physicists conjectured that CP symmetry might be a conserved quantity in all cases, even if parity alone is not. Yet, experiments such as those involving K-mesons in the 1960s revealed violations of CP symmetry as well, suggesting an even deeper subtlety in the fundamental operations of nature.

Understanding CP violation is crucial, as it contributes to the asymmetry between matter and antimatter in the universe and plays a significant role in explaining why our universe is predominantly matter and not a mixture of matter and antimatter.

The Role of Quantum Field Theory (QFT)

Quantum Field Theory, a cornerstone of modern physics, provides the framework for understanding and unifying these phenomena. QFT treats particles as excited states of underlying fields and allows physicists to use the tools of field theory to study interactions. In QFT, parity violation, quantum anomalies, and CP symmetry form essential parts of how we understand particle interactions, their transformations, and the fundamental forces at play.

In QFT, the behavior of symmetries and their violations can be systematically explored through rigorous mathematical formalisms such as Lagrangians and Feynman diagrams, which map out possible interactions. The comprehensive scope of QFT also aids in predicting outcomes of high-energy experiments and therefore plays an indispensable role in experimental physics.

- Parity Violation showcases how certain fundamental interactions deviate from expected mirror symmetries.
- Quantum Anomalies reveal the limitations of classical symmetries when applied to quantum theories.
- CP Symmetry and its violations point towards the inherent asymmetries in the laws of physics and their implications for our universe.

These concepts not only deepen our understanding of the universe at a fundamental level but also challenge us to rethink about symmetry and conservation laws in the quantum realm.

Applications and Impact in Modern Science

The phenomena of parity violation, quantum anomalies, and CP symmetry violations extend beyond mere theoretical interest and have profound applications in various fields of modern science. For instance, understanding these quantum effects is crucial in the advancement of technologies such as quantum computing and particle accelerators. Additionally, they play a significant role in cosmology, helping scientists understand the early stages of the universe and the predominance of matter over antimatter.

Medical imaging techniques, such as PET scans, also benefit from the principles of particle physics, including the understanding of antimatter. Moreover, research in these areas can lead to more effective treatments for diseases by harnessing the power of nuclear medicine and radiological treatments.

Challenges and Future Directions

Despite the advancements in field theory and particle physics, several challenges persist in fully understanding and applying the concepts of parity violation, quantum anomalies, and CP symmetry violations. One of the main challenges is the integration of these concepts with gravitational theory or crafting a theory that unifies all fundamental forces of nature, often referred to as the 'Theory of Everything'.

Future research in quantum field theory and its applications promises to not only address these challenges but also pave the way for new technologies and further our understanding of the universe. Innovations in experimental physics, such as more powerful particle accelerators and precise measurement tools, are expected to provide deeper insights into these subtle quantum phenomena.

Conclusion

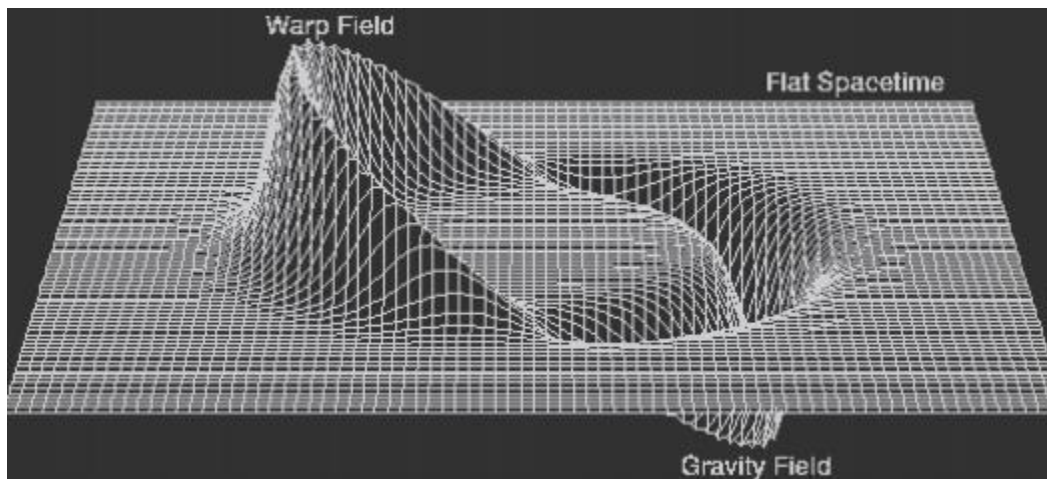
The exploration of complex quantum mechanics principles like parity violation, quantum anomalies, and CP symmetry offers profound insights into the fundamental nature of our universe. These concepts challenge the conventional notions of symmetry and conservation laws established by classical physics and open up a plethora of opportunities for theoretical and practical advancements. As we continue to unravel the mysteries of quantum field theory, we edge closer to a more complete understanding of the universe's building blocks and the forces that shape our reality. Engaging with these deep subjects not only enriches our knowledge base but also stimulates further research and development in quantum science, promising exciting prospects for future explorations.

Space-Time Metric Engineering

The use of metric engineering to **manipulate the structure of space and time**. Manipulation and fine control of space-time allows the creation of artificial wormholes, reactionless drives, and artificial universes.

Spacetime Metric Engineering

A theme that has come to the fore in advanced planning for long-range space exploration is the concept that empty space itself (the quantum vacuum, or spacetime metric) might be engineered so as to provide energy/thrust for future space vehicles. Although far-reaching, such a proposal is solidly grounded in modern physical theory, and therefore the possibility that matter/ vacuum interactions might be engineered for space-flight applications is not a priori ruled out. As examples, the current development of theoretical physics addresses such topics as warp drives, traversable wormholes and time machines that provide for such vacuum engineering possibilities. Our work provides a broad perspective of the physics and correlates/consequences of the engineering of the spacetime metric.



Alcubierre warp drive metric

The use of metric engineering to manipulate the structure of space and time. Manipulation and fine control of space-time allows the creation of artificial wormholes, reactionless drives, and artificial universes. However almost all forms of space-time engineering can only be successfully performed by
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Vector and Scalar Potentials through polarization

- PARTICLE PHYSICS
- [Theory of Relativity](#)
- [Statistical Mechanics](#)
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Helmholtz theorem. Scalar and vector potentials

Electromagnetic theory, lecture — III.

Helmholtz theorem. Vector and Scalar Potentials. This is an insect repellent which works on the basis of our understanding of electromagnetic wave. Colored light of various kinds are example of electromagnetic wave. They are governed by Maxwell equations and their deeper framework is the topic of our discussion in this lecture.

Topics covered

- A.** Formalism of electrodynamics — fundamental theorem
- B.** Application of Helmholtz theorem — to electrostatics
- C.** Application of Helmholtz theorem — to magnetostatics

Formalism of electrodynamics

Helmholtz theorem

In our previous lectures, [lecture](#) – I and [lecture](#) — II, we discussed the Maxwell’s equations in free space and in material media. We also discussed the boundary conditions which helps us solve for the $\vec{E}$ and $\vec{B}$ fields.

The $\vec{E}$ and $\vec{B}$ fields are vector fields and Maxwell equations involve differentiation of these vectors. So we have to deal with curl — $\vec{\nabla} \times$ and divergence — $\vec{\nabla} \cdot$, of these vectors — or vector fields, apart from any boundary conditions to be satisfied by these, as we saw in our last lecture [linked](#).

The Helmholtz theorems provides some useful relations and properties which helps us determine the $\vec{E}$ and $\vec{B}$ fields uniquely. It is important for us to understand the mathematical rigor and the physical vigor these equations provide in having an unified formal treatment that all of electrodynamics espouses.

One needs a basic proficiency in vector calculus to be able to grasp the inherent significance of these methods. To begin with one can go through the slides [here](#) — vector calculus, to have a reasonable hold on the vector calculus concepts.

There is a theorem which deals with the implications of curl of a vector.

Theorem 1

If curl of a vector field is zero — everywhere, then $\vec{F}$ can be written as the gradient — $\vec{\nabla}$ of a scalar field, also known as the scalar potential function V .

$$\vec{\nabla} \times \vec{F} = 0 \quad \Leftrightarrow \quad \vec{F} = -\vec{\nabla} V$$

Here the minus sign is just a convention.

a. Such fields, — $\vec{F}$ here, are known as curl-less or “irrotational” fields.

b. The curl is zero everywhere. I.e. $\vec{\nabla} \times \vec{F} = 0$

c. The quantity $\int_a^b \vec{F} \cdot d\vec{l}$ is independent of path — of *integration*, as long as limits a and b are fixed.

d. The quantity $\oint \vec{F} \cdot d\vec{l} = 0$ for closed paths or loops of integration.

e. The vector $\vec{F}$ can be written as the gradient of some scalar such that, $\vec{F} = -\vec{\nabla} V$.

f. If any one of the above statement is valid, it ensures all the others to be valid. That implies $c \implies a, b, d$ and so on.

g. Scalar potential V is not unique. Any function independent of position can be added to V without changing $\vec{F}$

Now there is a theorem which deals with the implications of divergence of a vector.

Theorem 2

If divergence — $\vec{\nabla} \cdot$, of a vector field $\vec{F}$ is zero — everywhere, then $\vec{F}$ can be expressed as the curl of a vector potential function $\vec{A}$.

$$\vec{\nabla} \cdot \vec{F} = 0 \quad \Leftrightarrow \quad \vec{F} = \vec{\nabla} \times \vec{A}$$

a. Such fields — $\vec{F}$ here, are known as *divergence-less* or “*solenoidal*” fields.

b. The divergence is *zero everywhere*. I.e. $\vec{\nabla} \cdot \vec{F} = 0$.

c. The quantity $\int \vec{F} \cdot d\vec{a}$ — is independent of *surface of integration*, as long as the boundary of the surface — a line, is fixed.

d. The quantity $\oint \vec{F} \cdot d\vec{a} = 0$ for closed surface of integration.

e. The vector $\vec{F}$ can be written as the curl of some vector such that, $\vec{F} = \vec{\nabla} \times \vec{A}$.

f. If any one of the above statement is valid, it ensures all the others to be valid. That implies $b \Rightarrow a, c, d$ and so on.

g. Vector potential $\vec{A}$ is not unique as gradients of any scalar function is curl-less. Gradients of any scalar function f can be added to the vector $\vec{A}$ and this transformation would leave the vector $\vec{F}$ unaltered.

I.e. if $\vec{A}' = \vec{A} + \vec{\nabla} f$ both new potential $\vec{A}'$ and old potential $\vec{A}$ would give rise to the same $\vec{F}$.

There is another mathematical result which has implications for both of the above theorems and we will state it.

Any general vector irrespective of whether this vector is divergence-less or *not*, and whether this vector is curl-less or *not*, can always be written as the sum of two vectors,

a. one vector which is the curl of some vector and

b. another vector which is the divergence of some scalar function.

In symbols:
$$\vec{F} = -\vec{\nabla} V + \vec{\nabla} \times \vec{A}$$

Application of the above theorems to 3 situations

We will study how the above theorems have a great deal of implication for almost all of the field of electromagnetic theory. These theorems are together known as Helmholtz theorems.

But we will study them under 3 situations — gradually moving up the ladder of generality, beginning with our familiar knowledge of the static electric and magnetic fields.

a. Electrostatics

b. Magnetostatics

and

c. Electrodynamics

Electrostatics

When electric charges are stationary the resulting electric fields lead to electrostatic behavior. Under these conditions, electric fields — $\vec{E}$, are always “irrotational“, i.e. curl-less, thus they satisfy conditions of — theorem 1, of Helmholtz theorem.

Because $\vec{\nabla} \times \vec{E} = 0$, all the other conditions are satisfied and a potential function known as scalar potential (V) can be defined.

$$\vec{\nabla} \times \vec{E} = 0 \quad \Rightarrow \quad V(\vec{r}) = - \int_{Ref}^{|\vec{r}|} \vec{E} \cdot d\vec{l}$$

Here Ref — for reference, on the lower limit of the integral sign stands for a particularly chosen location for the potential, from where all calculations are to be made. There are two standards for this idea to be implemented;

a. if charge distributions are finite, reference can be set to $|\vec{r}| = \infty$

b. if charge distributions are not finite, other means are to be explored to calculate $V(\vec{r})$ E.g. one should *not* set $|\vec{r}| = \infty$ on the lower limit of integration, in place of Ref, for an infinitely long cylinder.

The above boxed equation which we can define because curl of the electrostatic field $\vec{E}$ is zero, is an integral form of the scalar potential, V . The differential form of definition of scalar potential is then;

$$\vec{E} = -\vec{\nabla}V$$

In the electrostatics conditions, the potential formulation serves a very *useful* role, as 1 scalar equation is to be solved in lieu of 3 vector equations — we do not have to bother about the 3 vector components, which makes the problem cumbersome.

The two Maxwell equations — one vector and one scalar, $\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\epsilon_0}$ and $\vec{\nabla} \times \vec{E} = 0$ which are 4 equations in total, give rise to the Poisson's equation.

Poisson's equation:
$$\nabla^2 V = -\frac{\rho}{\epsilon_0}$$

When source term is absent i.e. $\rho = 0$, Poisson's equation turns into Laplace equation.

Laplace equation:
$$\nabla^2 V = 0$$

Potential can now be calculated as:

$$V(\vec{r}) = \frac{1}{4\pi\epsilon_0} \int \frac{\rho(\vec{r}')}{r_s} d\tau'$$

where $r_s \equiv |\vec{r}_s| = |\vec{r} - \vec{r}'|$, $\vec{r}_s$ is known as the separation vector. Now electric field can be calculated from $\vec{E} = -\vec{\nabla} V$. The expression is nothing but the Coulomb's law.

Magnetostatics

Magnetostatics problems follow a similar logic. The magnetostatic nature is defined by stationary currents or steady-currents. That means charge densities that produce the field must not vary in time.

Mathematically: $\frac{\partial \rho}{\partial t} = 0$. When used in the equation of continuity: $\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot \vec{j} = 0$, this means: $\vec{\nabla} \cdot \vec{j} = 0$. Thus the condition for magnetostatics is given by: $\vec{\nabla} \cdot \vec{j} = 0$.

The second Maxwell equation is: $\vec{\nabla} \cdot \vec{B} = 0$, i.e. magnetic fields are divergence-less in all situations.

According to theorem 2 of Helmholtz theorem then, magnetic field can always be written as curl of a vector potential $\vec{A}$, i.e. $\vec{B} = \vec{\nabla} \times \vec{A}$.

$\vec{A}$ is known as vector potential or magnetic vector potential.

By Ampere's law of Maxwell equations — i.e. $\vec{\nabla} \times \vec{B} = \mu_0 \vec{j}$, we have: $\vec{\nabla} \times \vec{B} = \vec{\nabla} \times (\vec{\nabla} \times \vec{A}) = \vec{\nabla}(\vec{\nabla} \cdot \vec{A}) - \nabla^2 \vec{A} = \mu_0 \vec{j}$.

We already discussed that the magnetic vector potential $\vec{A}$ is not unique. Because gradient of any scalar is curl-less.

By this freedom we can always find scalar λ , so that $\vec{\nabla} \cdot \vec{A} = 0$. If original vector potential $\vec{A}$ is not divergence-less we can add $\vec{\nabla}\lambda$ to it, to make it divergence-less.

Thus, $\vec{A}' = \vec{A} + \vec{\nabla}\lambda$ and $\vec{\nabla} \cdot \vec{A}' = \vec{\nabla} \cdot \vec{A} + \nabla^2\lambda$.

For $\vec{\nabla} \cdot \vec{A}' = 0$ we have $-\vec{\nabla} \cdot \vec{A} = \nabla^2\lambda$. This is nothing but Poisson's equation, as we have seen.

Remember Poisson's equation for electrostatics: $\nabla^2 V = -\frac{\rho}{\epsilon_0}$. So $\vec{\nabla} \cdot \vec{A}$ behaves like source: $\frac{\rho}{\epsilon_0}$.

As in the case of electrostatics case if $\vec{\nabla} \cdot \vec{A} \rightarrow 0$ at ∞ we have a solution to the Poisson's equation: $\nabla^2\lambda = -\vec{\nabla} \cdot \vec{A}$.

This solution is given by:

$$\lambda = \frac{1}{4\pi} \int \frac{\vec{\nabla} \cdot \vec{A}}{r_s} d\tau'$$

If the source term $\vec{\nabla} \cdot \vec{A}$ does not go to zero, (at ∞) we have to use other means as in the case of electrostatics.

It is always possible to find λ , to make $\vec{A}$ divergence-less.

Thus Ampere's law becomes: $\nabla^2 \vec{A} = -\mu_0 \vec{j}$. This is also Poisson's equation — actually 3 Poisson's equations, because its a vector equation.

If $\vec{j} \rightarrow 0$ at ∞ the solution is:

$$\vec{A}(\vec{r}) = \frac{\mu_0}{4\pi} \int \frac{\vec{j}(\vec{r}')}{r_s} d\tau'$$

Thus for steady currents we have:

$$\vec{B} = \vec{\nabla} \times \vec{A} = \frac{\mu_0}{4\pi} I \int \frac{d\vec{l}' \times \hat{r}_s}{r_s^2}$$

LONGITUDINAL SCALAR WAVES

Scalar waves are a type of electromagnetic wave that are **conceived as longitudinal waves**¹²³. Unlike transverse waves, such as radio waves or light waves, scalar waves are longitudinal in nature². Scalar waves vibrate in line with the direction of propagation, unlike the transversal waves of electromagnetism, which move up and down perpendicularly to the direction of propagation¹. Scalar waves are hypothetical waves that differ from the conventional electromagnetic transverse waves by one oscillation level parallel to the direction of propagation³

What are Scalar Waves?

Scalar waves are conceived as longitudinal waves, as are sound waves. Unlike the transversal waves of electromagnetism, which move up and down perpendicularly to the direction of propagation, longitudinal waves vibrate in line with the direction of propagation. Transversal waves can be observed in water ripples: the ripples move up and down as the overall waves move outward, such that there are two actions; one moving up and down, and the other propagating in a specific direction outward.

Technically speaking, scalar electromagnetic waves have magnitude but no direction, since they are imagined to be the result of two electromagnetic waves that are 180 degrees out of phase with one another, which leads to both signals being canceled out. This results in a kind of 'pressure wave'.

Mathematical physicist James Clerk Maxwell, in his original mathematical equations concerning electromagnetism, established the theoretical existence of scalar electromagnetic waves. After his death, however, later physicists assumed these equations were meaningless,

since scalar waves had not been empirically observed and repeatedly verified among the scientific community at large.

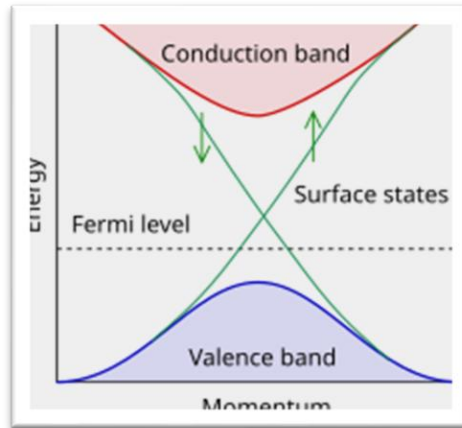
Vibrational, or subtle energetic research, however, has helped advance our understanding of scalar electromagnetic waves. One important discovery states that there are many different types of scalar waves, not just those of the electromagnetic variety. For example, there are vital scalar waves (corresponding with the vital or “qi” body), emotional scalar waves, mental scalar waves, causal scalar waves, and so forth. In essence, as far as we are aware, all “subtle” energies are made up of various types of scalar waves and scalar wave energy.

Some general properties of scalar electromagnetic waves (of the beneficial kind) include:

- Travel faster than the speed of light.
- Seem to transcend space and time.
- Cause the molecular structure of water to become coherently reordered.
- Positively increase immune function in mammals.
- Are involved in the formation process in nature.

Not all scalar waves, or subtle energies, are beneficial to living systems. Electromagnetism of the 60 Hz AC variety, for example, emanates a secondary longitudinal/scalar wave that is typically detrimental to living systems. Subtle Energy Science’s energetic encoding technology and scalar-wave entrainment effectively cancel this detrimental wave and transmute it into a beneficial wave.

Topological insulator



An (informal) phase diagram with topological insulators, trivial insulators, and conductors. There is no path from the topological insulators to the trivial insulators that

does not cross the conducting phase. The diagram depicts a topological invariant, since there are two "islands" of insulators. An idealized [band structure](#) for a 3D time-reversal symmetric topological insulator. The [Fermi level](#) falls within the bulk band gap which is traversed by topologically-protected spin-textured Dirac surface states.^{[1][2]}

A **topological insulator** is a material whose interior behaves as an [electrical insulator](#) while its surface behaves as an [electrical conductor](#),^[3] meaning that electrons can only move along the surface of the material.

A topological insulator is an insulator for the same reason a "[trivial](#)" (ordinary) insulator is: there exists an [energy gap](#) between the [valence and conduction bands](#) of the material. But in a topological insulator, these bands are, in an informal sense, "twisted", relative to a trivial insulator.^[4] The topological insulator cannot be [continuously](#) transformed into a trivial one without untwisting the bands, which closes the band gap and creates a conducting state. Thus, due to the continuity of the underlying field, the [border](#) of a topological insulator with a trivial insulator (including [vacuum](#), which is topologically trivial) is forced to support a conducting state.^[5]

Since this results from a global property of the topological insulator's [band structure](#), local (symmetry-preserving) perturbations cannot damage this surface state.^[6] This is unique to topological insulators: while ordinary insulators can also support conductive surface states, only the surface states of topological insulators have this robustness property.

This leads to a more formal definition of a topological insulator: an insulator which cannot be [adiabatically](#) transformed into an ordinary insulator without passing through an intermediate conducting state.^[5] In other words, topological insulators and trivial insulators are separate regions in the [phase diagram](#), connected only by conducting phases. In this way, topological insulators provide an example of a [state of matter](#) not described by the [Landau symmetry-breaking theory](#) that defines ordinary states of matter.^[6]

The properties of topological insulators and their surface states are highly dependent on both the dimension of the material and its underlying [symmetries](#), and can be classified using the so-called [periodic table of topological insulators](#). Some combinations of dimension and symmetries forbid topological insulators completely.^[7] All topological insulators have at least [U\(1\) symmetry](#) from particle number conservation, and often have [time-reversal symmetry](#) from the absence of a magnetic field. In this way, topological insulators are an example of [symmetry-protected topological order](#).^[8] So-

called "topological invariants", taking values in or , allow classification of insulators as trivial or topological, and can be computed by various methods.^[7]

The surface states of topological insulators can have exotic properties. For example, in time-reversal symmetric 3D topological insulators, surface states have their [spin](#) locked at a right-angle to their momentum (spin-momentum locking). At a given energy the only other available electronic states have different spin, so ["U"-turn scattering](#) is strongly suppressed and conduction on the surface is highly metallic.

Despite their origin in quantum mechanical systems, analogues of topological insulators can also be found in classical media. There exist [photonic](#),^[9] [magnetic](#),^[10] and [acoustic](#)^[11] topological insulators, among others.

Prediction

The first models of 3D topological insulators were proposed by B. A. Volkov and O. A. Pankratov in 1985,^[12] and subsequently by Pankratov, S. V. Pakhomov, and Volkov in 1987.^[13] Gapless 2D Dirac states were shown to exist at the band inversion contact in [PbTe/SnTe](#)^[12] and [HgTe/CdTe](#)^[13] heterostructures. Existence of interface Dirac states in HgTe/CdTe was experimentally verified by [Laurens W. Molenkamp's](#) group in 2D topological insulators in 2007.^[14]

Later sets of theoretical models for the 2D topological insulator (also known as the quantum spin Hall insulators) were proposed by [Charles L. Kane](#) and [Eugene J. Mele](#) in 2005,^[15] and also by [B. Andrei Bernevig](#) and [Shoucheng Zhang](#) in

2006.^[16] The topological invariant was constructed and the importance of the time reversal symmetry was clarified in the work by Kane and Mele.^[17] Subsequently, Bernevig, Taylor L. Hughes and Zhang made a theoretical prediction that 2D topological insulator with one-dimensional (1D) helical edge states would be realized in quantum wells (very thin layers) of mercury telluride sandwiched between cadmium

telluride.^[18] The transport due to 1D helical edge states was indeed observed in the experiments by Molenkamp's group in 2007.^[14]

Although the topological classification and the importance of time-reversal symmetry was pointed in the 2000s, all the necessary ingredients and physics of topological insulators were already understood in the works from the 1980s.

In 2007, it was predicted that 3D topological insulators might be found in binary compounds involving [bismuth](#),^{[19][20][21][22]} and in particular "strong topological insulators" exist that cannot be reduced to multiple copies of the [quantum spin Hall state](#).^[23]

Experimental realization

2D Topological insulators were first realized in system containing [HgTe](#) quantum wells sandwiched between [cadmium telluride](#) in 2007.

The first 3D topological insulator to be realized experimentally was [Bi_{1-x}Sb_x](#).^{[24][25][26]} Bismuth in its pure state, is a [semimetal](#) with a small electronic band gap. Using [angle-resolved photoemission spectroscopy](#), and many other measurements, it was observed that Bi_{1-x}Sb_x alloy exhibits an odd [surface state](#) (SS) crossing between any pair of [Kramers](#) points and the bulk features massive Dirac fermions.^[25] Additionally, bulk Bi_{1-x}Sb_x has been predicted to have 3D [Dirac particles](#).^[27] This prediction is of particular interest due to the observation of charge [quantum Hall fractionalization](#) in 2D graphene^[28] and pure bismuth.^[29]

Shortly thereafter symmetry-protected surface states were also observed in pure [antimony](#), [bismuth selenide](#), [bismuth telluride](#) and [antimony telluride](#) using [angle-resolved photoemission spectroscopy](#) (ARPES).^{[30][31][32][33][34]} and [bismuth selenide](#).^{[34][35]} Many semiconductors within the large family of [Heusler materials](#) are now believed to exhibit topological surface states.^{[36][37]} In some of these materials, the Fermi level actually falls in either the conduction or valence bands due to naturally-occurring defects, and must be pushed into the bulk gap by [doping](#) or gating.^{[38][39]} The surface states of a 3D topological insulator is a new type of [two-dimensional electron gas](#) (2DEG) where the electron's spin is locked to its linear momentum.^[31]

Fully bulk-insulating or intrinsic 3D topological insulator states exist in Bi-based materials as demonstrated in surface transport measurements.^[40] In a new Bi based chalcogenide (Bi_{1.1}Sb_{0.9}Te₂S) with slightly Sn - doping, exhibits an intrinsic semiconductor behavior with Fermi energy and Dirac point lie in the bulk gap and the surface states were probed by the charge transport experiments.^[41]

It was proposed in 2008 and 2009 that topological insulators are best understood not as surface conductors per se, but as bulk 3D magnetoelectrics with a quantized [magnetoelectric](#) effect.^{[42][43]} This can be revealed by placing topological insulators in magnetic field. The effect can be described in language similar to that of the hypothetical [axion particle](#) of particle physics.^[44] The effect was reported by

researchers at [Johns Hopkins University](#) and [Rutgers University](#) using [THz spectroscopy](#) who showed that the Faraday rotation was quantized by the fine structure constant.^[45]

In 2012, topological [Kondo](#) insulators were identified in [samarium hexaboride](#), which is a bulk insulator at low temperatures.^{[46][47]}

In 2014, it was shown that magnetic components, like the ones in [spin-torque computer memory](#), can be manipulated by topological insulators.^{[48][49]} The effect is related to [metal–insulator transitions](#) ([Bose–Hubbard model](#)).^[citation needed]

Floquet topological insulators

Topological insulators are challenging to synthesize, and limited in topological phases accessible with solid-state materials.^[50] This has motivated the search for topological phases on the systems that simulate the same principles underlying topological insulators. Discrete time quantum walks (DTQW) have been proposed for making Floquet topological insulators (FTI). This periodically driven system simulates an effective ([Floquet](#)) Hamiltonian that is topologically nontrivial.^[51] This system replicates the effective Hamiltonians from all universal classes of 1- to 3-D topological insulators.^{[52][53][54][55]} Interestingly, topological properties of Floquet topological insulators could be controlled via an external periodic drive rather than an external magnetic field. An atomic lattice empowered by distance selective Rydberg interaction could simulate different classes of FTI over a couple of hundred sites and steps in 1, 2 or 3 dimensions.^[55] The long-range interaction allows designing topologically ordered periodic boundary conditions, further enriching the realizable topological phases.^[55]

Properties and applications

Spin-momentum locking^[31] in the topological insulator allows symmetry-protected surface states to host [Majorana particles](#) if superconductivity is induced on the surface of 3D topological insulators via proximity effects.^[56] (Note that Majorana zero-mode can also appear without topological insulators.^[57]) The non-trivialness of topological insulators is encoded in the existence of a gas of [helical Dirac fermions](#). Dirac particles which behave like massless relativistic fermions have been observed in 3D topological insulators. Note that the gapless surface states of topological insulators differ from those in the [quantum Hall effect](#): the gapless surface states of topological insulators are symmetry-protected (i.e., not topological), while the gapless surface states in quantum Hall effect are topological (i.e., robust against any local perturbations that can break all

the symmetries). The topological invariants cannot be measured using traditional transport methods, such as spin Hall conductance, and the transport is not quantized by

the invariants. An experimental method to measure topological invariants was

demonstrated which provide a measure of the topological order.^[58] (Note that the

term [topological order](#) has also been used to describe the [topological order](#) with

emergent [gauge theory](#) discovered in 1991.^{[59][60]} More generally (in what is known as the *ten-fold way*) for each spatial dimensionality, each of the ten Altland—Zirnbauer symmetry classes of [random Hamiltonians](#) labelled by the type of discrete symmetry (time-reversal symmetry, particle-hole symmetry, and chiral symmetry) has a

corresponding group of topological invariants (either , or trivial) as described by the [periodic table of topological invariants](#).^[61]

The most promising applications of topological insulators are spintronic devices and dissipationless [transistors](#) for [quantum computers](#) based on the [quantum Hall effect](#)^[14] and [quantum anomalous Hall effect](#).^[62] In addition, topological insulator materials have also found practical applications in advanced [magnetoelectronic](#) and [optoelectronic](#) devices.^{[63][64]}

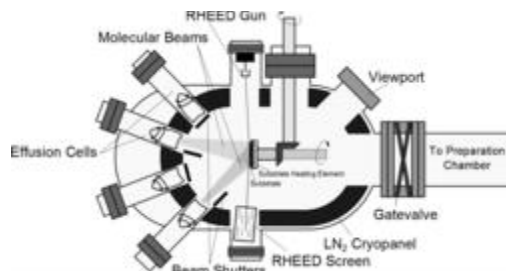
Thermoelectrics

Some of the most well-known topological insulators are also [thermoelectric materials](#), such as Bi_2Te_3 and its alloys with Bi_2Se_3 (n-type thermoelectrics) and Sb_2Te_3 (p-type thermoelectrics).^[65] High thermoelectric power conversion efficiency is realized in materials with low thermal conductivity, high electrical conductivity, and high [Seebeck coefficient](#) (i.e., the incremental change in voltage due to an incremental change in temperature). Topological insulators are often composed of heavy atoms, which tends to lower thermal conductivity and are therefore beneficial for thermoelectrics. A recent study also showed that good electrical characteristics (i.e., high electrical conductivity and Seebeck coefficient) can arise in topological insulators due to warping of the bulk band structure, which is driven by band inversion.^[66] Often, the electrical conductivity and Seebeck coefficient are conflicting properties of thermoelectrics and difficult to optimize simultaneously. Band warping, induced by band inversion in a topological insulator, can mediate the two properties by reducing the effective mass of electrons/holes and increasing the valley degeneracy (i.e., the number of electronic bands that are contributing to charge transport). As a result, topological insulators are generally interesting candidates for thermoelectric applications.

Synthesis

Topological insulators can be grown using different methods such as [metal-organic chemical vapor deposition](#) (MOCVD),^[67]

[physical vapor deposition](#) (PVD),^[68] solvothermal synthesis,^[69] sonochemical technique^[70] and [molecular beam epitaxy](#)



Schematic of the components of a MBE system

(MBE).^[34] MBE has so far been the most common experimental technique. The growth of thin film topological insulators is governed by weak [van der Waals interactions](#).^[71] The weak interaction allows to exfoliate the thin film from bulk crystal with a clean and perfect surface. The van der Waals interactions in epitaxy also known as van der Waals epitaxy (VDWE), is a phenomenon governed by weak van der Waals interactions between layered materials of different or same elements^[72] in which the materials are stacked on top of each other. This approach allows the growth of layered topological insulators on other substrates for [heterostructure](#) and [integrated circuits](#).^[72]

MBE growth of topological insulators

Molecular beam epitaxy (MBE) is an [epitaxy](#) method for the growth of a crystalline material on a crystalline substrate to form an ordered layer. MBE is performed in [high vacuum](#) or [ultra-high vacuum](#), the elements are heated in different electron beam evaporators until they [sublime](#). The gaseous elements then condense on the wafer where they react with each other to form [single crystals](#).

MBE is an appropriate technique for the growth of high quality single-crystal films. In order to avoid a huge [lattice mismatch](#) and [defects](#) at the interface, the substrate and thin film are expected to have similar lattice constants. MBE has an advantage over other methods due to the fact that the synthesis is performed in high vacuum hence resulting in less contamination. Additionally, lattice defect is reduced due to the ability to influence the growth rate and the ratio of species of source materials present at the substrate interface.^[73] Furthermore, in MBE, samples can be grown layer by layer which results in flat surfaces with smooth interface for engineered heterostructures. Moreover, MBE synthesis technique benefits from the ease of moving a topological insulator sample from the growth chamber to a characterization chamber such as angle-resolved photoemission spectroscopy (ARPES) or [scanning tunneling microscopy](#) (STM) studies.^[74]

Due to the weak van der Waals bonding, which relaxes the lattice-matching condition, TI can be grown on a wide variety of substrates^[75] such as Si(111),^{[76][77]} [Al](#)

[₂O](#)

[₃](#), [GaAs](#)(111),^[78]

[InP](#)(111), [CdS](#)(0001) and [Y](#)

[₃Fe](#)

[₅O](#)

[12](#) .

PVD growth of topological insulators

The physical vapor deposition (PVD) technique does not suffer from the disadvantages of the exfoliation method and, at the same time, it is much simpler and cheaper than the fully controlled growth by molecular-beam epitaxy. The PVD method enables a reproducible synthesis of single crystals of various layered quasi-two-dimensional materials including topological insulators (i.e., Bi

₂Se

₃, Bi

₂Te

₃).^[79] The resulted single crystals have a well-defined crystallographic orientation; their composition, thickness, size, and the surface density on the desired substrate can be controlled. The thickness control is particularly important for 3D TIs in which the trivial (bulky) electronic channels usually dominate the transport properties and mask the response of the topological (surface) modes. By reducing the thickness, one lowers the contribution of trivial bulk channels into the total conduction, thus forcing the topological modes to carry the electric current.^[80]

Bismuth-based topological insulators

Thus far, the field of topological insulators has been focused on bismuth and antimony [chalcogenide](#) based materials such as Bi

₂Se

₃, Bi

₂Te

₃, Sb

₂Te

₃ or [Bi_{1-x}Sb_x](#), Bi_{1.1}Sb_{0.9}Te₂S.^[41] The choice of chalcogenides is related to the van der Waals relaxation of the lattice matching strength which restricts the number of materials and substrates.^[73] Bismuth chalcogenides have been studied extensively for TIs and their applications in [thermoelectric materials](#). The van der Waals interaction in TIs exhibit important features due to low surface energy. For instance, the surface of [Bi](#)

₂Te

₃ is usually terminated by Te due to its low surface energy.^[34]

Bismuth chalcogenides have been successfully grown on different substrates. In particular, Si has been a good substrate for the successful growth of Bi

₂Te

₃. However, the use of sapphire as substrate has not been so encouraging due to a large mismatch of about 15%.^[81] The selection of appropriate substrate can improve the overall properties of TI. The use of buffer layer can reduce the lattice match hence improving the electrical properties of TI.^[81] Bi

₂Se

₃ can be grown on top of various Bi_{2-x}In_xSe₃ buffers. Table 1 shows [Bi](#)

₂Se

₃, Bi

₂Te

³, [Sb](#)
²[Te](#)

³ on different substrates and the resulting lattice mismatch. Generally, regardless of the substrate used, the resulting films have a textured surface that is characterized by pyramidal single-crystal domains with quintuple-layer steps. The size and relative proportion of these pyramidal domains vary with factors that include film thickness, lattice mismatch with the substrate and interfacial chemistry-dependent film nucleation. The synthesis of thin films have the stoichiometry problem due to the high vapor pressures of the elements. Thus, binary tetradymites are extrinsically doped as n-type (Bi

²Se

³, Bi

²Te

³) or p-type (Sb

²Te

³).^[73] Due to the weak van der Waals bonding, graphene is one of the preferred substrates for TI growth despite the large lattice mismatch.

Lattice mismatch of different substrates^[75]

Substrate	Bi ² Se ³ %	Bi ² Te ³ %	Sb ² Te ³ %
graphene	−40.6	−43.8	−42.3
Si	−7.3	−12.3	−9.7
CaF ₂	−6.8	−11.9	−9.2
GaAs	−3.4	−8.7	−5.9
CdS	−0.2	−5.7	−2.8
InP	0.2	−5.3	−2.3
BaF ₂	5.9	0.1	2.8
CdTe	10.7	4.6	7.8
Al ₂ O ₃	14.9	8.7	12.0
SiO ₂	18.6	12.1	15.5

Identification

The first step of topological insulators identification takes place right after synthesis, meaning without breaking the vacuum and moving the sample to an atmosphere. That could be done by using angle-resolved photoemission spectroscopy (ARPES) or scanning tunneling microscopy (STM) techniques.^[74] Further measurements includes

structural and chemical probes such as X-ray diffraction and energy-dispersive spectroscopy but depending on the sample quality, the lack of sensitivity could remain.

Transport measurements cannot uniquely pinpoint the topology by definition of the state.

Classification

Main article: [Periodic table of topological invariants](#)

[Bloch's theorem](#) allows a full characterization of the wave propagation properties of a material by assigning a matrix to each wave vector in the [Brillouin zone](#).

Mathematically, this assignment creates a [vector bundle](#). Different materials will have different wave propagation properties, and thus different vector bundles. If we consider all insulators (materials with a band gap), this creates a space of vector bundles. It is the topology of this space (modulo trivial bands) from which the "topology" in topological insulators arises.^[7]

Specifically, the number of [connected components](#) of the space indicates how many different "islands" of insulators exist amongst the metallic states. Insulators in the connected component containing the vacuum state are identified as "trivial", and all other insulators as "topological". The connected component in which an insulator lies can be identified with a number, referred to as a "topological invariant".^[7]

This space can be restricted under the presence of symmetries, changing the resulting topology. Although [unitary](#) symmetries are usually significant in quantum mechanics, they have no effect on the topology here.^[82] Instead, the three symmetries typically considered are time-reversal symmetry, particle-hole symmetry, and chiral symmetry (also called sublattice symmetry). Mathematically, these are represented as, respectively: an [anti-unitary operator](#) which commutes with the [Hamiltonian](#); an anti-unitary operator which [anti-commutes](#) with the Hamiltonian; and a unitary operator which anti-commutes with the Hamiltonian. All combinations of the three together with each spatial dimension result in the so-called [periodic table of topological insulators](#).^[7]

Future developments

The field of topological insulators still needs to be developed. The best bismuth chalcogenide topological insulators have about 10 meV bandgap variation due to the charge. Further development should focus on the examination of both: the presence of high-symmetry electronic bands and simply synthesized materials. One of the candidates is [half-Heusler compounds](#).^[74] These crystal structures can consist of a large number of elements. Band structures and energy gaps are very sensitive to the valence configuration; because of the increased likelihood of intersite exchange and disorder, they are also very sensitive to specific crystalline configurations. A nontrivial band structure that exhibits band ordering analogous to that of the known 2D and 3D TI materials was predicted in a variety of 18-electron half-Heusler compounds using first-

principles calculations.^[83] These materials have not yet shown any sign of intrinsic topological insulator behavior in actual experiments.

Understanding High-k Dielectrics in Modern Electronics

High- κ dielectric

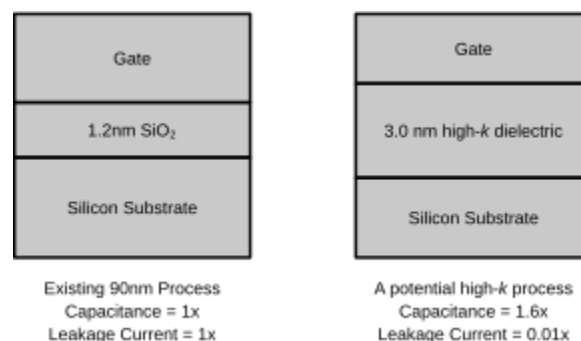
In the [semiconductor industry](#), the term **high- κ dielectric** refers to a material with a high [dielectric constant](#) (κ , [kappa](#)), as compared to [silicon dioxide](#). High- κ dielectrics are used in [semiconductor manufacturing](#) processes where they are usually used to replace a silicon dioxide [gate dielectric](#) or another dielectric layer of a device. The implementation of high- κ gate dielectrics is one of several strategies developed to allow further miniaturization of microelectronic components, colloquially referred to as extending [Moore's Law](#).

Sometimes these materials are called "high-k" (pronounced "high kay"), instead of "high- κ " (high kappa).

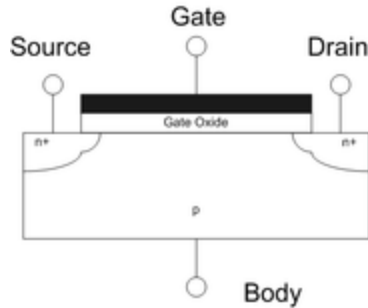
Need for high- κ materials

[Silicon dioxide](#) (SiO_2) has been used as a [gate oxide](#) material for decades. As [metal-oxide-semiconductor field-effect transistors](#) (MOSFETs) have decreased in size, the thickness of the silicon dioxide gate dielectric has steadily decreased to increase the [gate capacitance](#) (per unit area) and thereby drive current (per device width), raising device performance. As the thickness scales below 2 [nm](#), leakage currents due to [tunneling](#) increase drastically, leading to high power consumption and reduced device reliability. Replacing the silicon dioxide gate dielectric with a high- κ material allows increased gate thickness thus decreasing gate capacitance without the associated leakage effects.

First principles



Conventional silicon dioxide gate dielectric structure compared to a potential high- κ dielectric structure where $\kappa = 16$ Cross-section of an n-channel [MOSFET](#) transistor showing the gate oxide dielectric



The gate oxide in a [MOSFET](#) can be modeled as a parallel plate capacitor. Ignoring quantum mechanical and depletion effects from the [Si](#) substrate and gate, the [capacitance](#) C of this parallel plate [capacitor](#) is given by

where

- A is the capacitor area
- κ is the [relative dielectric constant](#) of the material (3.9 for [silicon dioxide](#))
- ϵ_0 is the [permittivity of free space](#)
- t is the thickness of the capacitor oxide insulator

Since leakage limitation constrains further reduction of t , an alternative method to increase gate capacitance is to alter κ by replacing silicon dioxide with a high- κ material. In such a scenario, a thicker gate oxide layer might be used which can reduce the [leakage current](#) flowing through the structure as well as improving the gate dielectric [reliability](#).

Gate capacitance impact on drive current

[\[edit\]](#)

The drain current I_D for a [MOSFET](#) can be written (using the gradual channel approximation) as

where

- W is the width of the transistor channel
- L is the channel length
- μ is the channel carrier mobility (assumed constant here)
- C_{inv} is the capacitance density associated with the gate dielectric when the underlying channel is in the inverted state

- V_G is the voltage applied to the transistor gate
- V_{th} is the [threshold voltage](#)

The term $V_G - V_{th}$ is limited in range due to reliability and room temperature operation constraints, since a too large V_G would create an undesirable, high electric field across the oxide. Furthermore, V_{th} cannot easily be reduced below about 200 mV, because leakage currents due to increased oxide leakage (that is, assuming high- κ dielectrics are not available) and [subthreshold conduction](#) raise stand-by power consumption to unacceptable levels. (See the industry roadmap,^[1] which limits threshold to 200 mV, and Roy *et al.* ^[2]). Thus, according to this simplified list of factors, an increased $I_{D,sat}$ requires a reduction in the channel length or an increase in the gate dielectric capacitance.

Materials and considerations

Replacing the silicon dioxide gate dielectric with another material adds complexity to the manufacturing process. Silicon dioxide can be formed by [oxidizing](#) the underlying silicon, ensuring a uniform, conformal oxide and high interface quality. As a consequence, development efforts have focused on finding a material with a requisitely high dielectric constant that can be easily integrated into a manufacturing process. Other key considerations include [band](#) alignment to [silicon](#) (which may alter leakage current), film morphology, thermal stability, maintenance of a high [mobility](#) of charge carriers in the channel and minimization of electrical defects in the film/interface. Materials which have received considerable attention are [hafnium silicate](#), [zirconium silicate](#), [hafnium dioxide](#) and [zirconium dioxide](#), typically deposited using [atomic layer deposition](#).

It is expected that defect states in the high- κ dielectric can influence its electrical properties. Defect states can be measured for example by using zero-bias thermally stimulated current, zero-temperature-gradient zero-bias thermally stimulated [current spectroscopy](#),^{[3][4]} or [inelastic electron tunneling spectroscopy](#) (IETS).

Use in industry

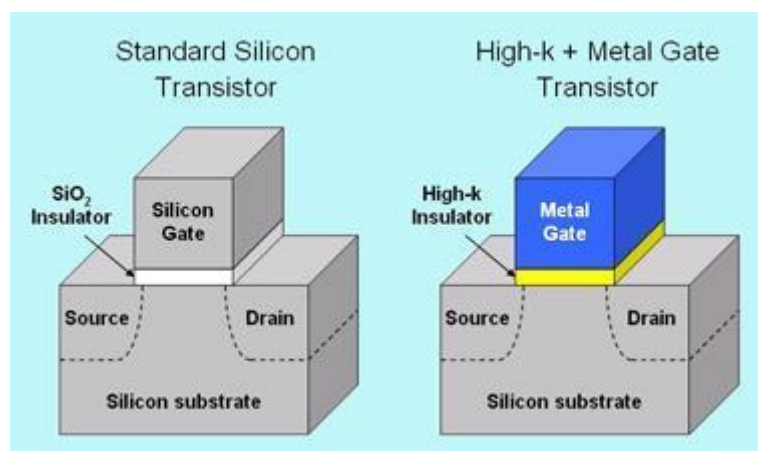
Industry has employed [oxynitride](#) gate dielectrics since the 1990s, wherein a conventionally formed silicon oxide dielectric is infused with a small amount of nitrogen. The nitride content subtly raises the dielectric constant and is thought to offer other advantages, such as resistance against dopant diffusion through the gate dielectric.

In 2000, [Gurtej Singh Sandhu](#) and Trung T. Doan of [Micron Technology](#) initiated the development of [atomic layer deposition](#) high- κ [films](#) for [DRAM](#) memory devices. This helped drive cost-effective implementation of [semiconductor memory](#), starting with [90-nm node](#) DRAM.^{[5][6]}

In early 2007, [Intel](#) announced the deployment of [hafnium](#)-based high-k dielectrics in conjunction with a metallic gate for components built on [45 nanometer](#) technologies, and has shipped it in the 2007 processor series codenamed [Penryn](#).^{[7][8]} At the same time, [IBM](#) announced plans to transition to high-k materials, also hafnium-based, for some products in 2008. While not identified, the most likely dielectric used in such applications are some form of nitrided hafnium silicates (HfSiON). HfO₂ and HfSiO are susceptible to crystallization during dopant activation annealing. [NEC](#) Electronics has also announced the use of a HfSiON dielectric in their 55 nm *UltimateLowPower* technology.^[9] However, even HfSiON is susceptible to trap-related leakage currents, which tend to increase with stress over device lifetime. This leakage effect becomes more severe as hafnium concentration increases. There is no guarantee, however, that hafnium will serve as a de facto basis for future high-k dielectrics. The 2006 [ITRS](#) roadmap predicted the implementation of high-k materials to be commonplace in the industry by 2010.

High-k Dielectrics: Key to Smaller, More Efficient Semiconductors

Definition: High-k dielectrics are materials characterized by a high dielectric constant, a technical measure of a material's ability to store electrical charge in an electric field. In simpler terms, think of the dielectric constant as a way to gauge how good a material is at holding electrical energy, similar to how a sponge's quality is determined by its ability to absorb water. The higher this "sponge's" capacity, the more electrical charge it can hold, making high-k dielectrics crucial for making electronic devices smaller, faster, and more efficient.



*A hafnium oxide insulator and metal gate have helped Intel to shrink their chips even further.
(Image: Intel)*

Overview of High-k Dielectrics

In the field of semiconductor fabrication, high-k dielectrics represent a class of materials with a dielectric constant significantly higher than traditional silicon dioxide. These materials are crucial for achieving transistor scaling, enabling the reduction of gate length in [transistors](#) without increasing leakage current.

The Role of High-k Dielectrics in Semiconductor Devices

High-k dielectrics are primarily utilized in the gate dielectric layer of metal-oxide-semiconductor field-effect transistors ([MOSFETs](#)). Their high dielectric constant allows for a thicker gate oxide equivalent, critical for leakage current reduction while maintaining the electric field effect required for transistor operation.

Significance in Transistor Scaling and Semiconductor Fabrication

The advent of high-k materials has been a game-changer in semiconductor fabrication, directly addressing the challenges of transistor scaling. As devices become smaller, managing leakage current while maintaining performance becomes paramount. High-k dielectrics facilitate this balance, making them indispensable in the evolution of compact, high-performance semiconductor devices.

Advantages of Incorporating High-k Dielectrics

- **Enabling Transistor Scaling:** High-k materials are key to continuing Moore's Law, allowing for smaller transistor dimensions with reduced power consumption and leakage current.
- **Improving Semiconductor Fabrication:** They offer new pathways in semiconductor fabrication, providing solutions to traditional limitations faced by silicon dioxide and other materials.
- **Leakage Current Reduction:** One of the most critical advantages of high-k dielectrics is their ability to significantly reduce leakage current, enhancing device reliability and energy efficiency.

Challenges in Integration and Application

- **Compatibility with Semiconductor Processes:** Integrating high-k dielectrics into semiconductor fabrication processes requires careful consideration of material compatibility and process modifications.
- **Advanced Deposition Techniques:** Employing techniques such as [atomic layer deposition](#) (ALD) is essential for the precise application of high-k materials, ensuring uniformity and optimal performance.

Emerging High-k Materials and Their Applications

While hafnium oxide (HfO_2) and zirconium oxide (ZrO_2) are well-known high-k materials, recent research has expanded the list to include tantalum oxide (Ta_2O_5), aluminum oxide (Al_2O_3), and yttrium oxide (Y_2O_3). These materials offer different advantages in terms of dielectric properties, stability, and compatibility with semiconductor fabrication processes. Their precise

application can vary, but they are primarily used to enhance transistor performance, enable further transistor scaling, and reduce leakage currents in semiconductor devices. The choice of material often depends on the specific requirements of the semiconductor fabrication process and the desired properties of the final electronic device.

Further Exploration and Learning

IEEE Transactions on Electron Devices, [High-k Gate Dielectric Materials: Applications with Advanced Metal Oxide Semiconductor Field Effect Transistors \(MOSFETs\)](#)

IEEE Transactions on Device and Materials Reliability, [Review on high-k dielectrics reliability issues](#)

Materials Today: Proceedings, [A review on effect of various high-k dielectric materials on the performance of FinFET device](#)

curved spacetime. An alternative approach is presented here, based on treating the vacuum as a polarizable medium. Beyond simply reproducing the standard weak-field predictions of GR, the polarizable vacuum (PV) approach provides additional insight into what is meant by a curved metric. For the strong field case, a divergence of predictions in the two formalisms (GR vs. PV) provides fertile ground for both laboratory and astrophysical tests.

Polarizable-Vacuum (PV) Approach to General Relativity

[H. E. Puthoff](#)

[Foundations of Physics](#) 32 (6):927-943 (2002) Copy $\text{\LaTeX}$

Abstract

Standard pedagogy treats topics in general relativity (GR) in terms of tensor formulations in curved space-time. An alternative approach based on treating the vacuum as a polarizable medium is presented here. The polarizable vacuum (PV) approach to GR, derived from a model by Dicke and related to the “ $\text{TH}\epsilon\mu$ ” formalism used in comparative studies of gravitational theories, provides additional insight into what is meant by a curved metric. While reproducing the results predicted by GR for standard (weak-field) astrophysical conditions, for strong fields a divergence of predictions in the two formalisms (GR vs. PV) provides fertile ground for both laboratory and astrophysical tests to compare the two approaches

Extended Electrodynamics: A Brief Review

[Stoil Donev](#), [Maria Tashkova](#)

This paper presents a brief review of the newly developed \emph{Extended Electrodynamics}. The relativistic and non-relativistic approaches to the extension of Maxwell equations are considered briefly, and the further study is carried out in relativistic terms in Minkowski space-time. The non-linear vacuum solutions are considered and fully described. It is specially pointed out that solitary waves with various, in fact arbitrary, spatial structure and photon-like propagation properties exist. The \{it null\} character of all non-linear vacuum solutions is established and extensively used further. Coordinate-free definitions are given to the important quantities \{it amplitude\} and \{it phase\}. The new quantity, named \{it scale factor\}, is introduced and used as a criterion for availability of rotational component of propagation of some of the nonlinear, i.e. nonmaxwellian, vacuum solutions. The group structure properties of the nonlinear vacuum solutions are analyzed in some detail, showing explicitly the connection of the vacuum solutions with some complex valued functions. Connection-curvature interpretations are given and a special attention is paid to the curvature interpretation of the intrinsic rotational (spin) properties of some of the nonlinear solutions. Several approaches to coordinate-free local description and computation of the integral spin momentum are considered. Finally, a large family of nonvacuum spatial soliton-like solutions is explicitly written down, and a procedure to get $(3+1)$ versions of the known $(1+1)$ soliton solutions is obtained.

