

QUANTUM VACUUM INTERACTION FOR PROPULSION and ZERO POINT ENERGY

Quantum Propulsion: Background and Practical Applications

Introduction

Present-day aerospace technology is in a deep crisis. The speed and lifting capacity of modern airplanes and spacecraft is notoriously limited with no prospects of improvement. The chemical fuel rocket and jet engines played their historical role well, but they have no prospects of improving. Quantum Propulsion Technologies Ltd. team is developing new types of propulsion systems and space vehicles that will revolutionize air travel and space exploration. They will act as the next stepping stone in the development of our civilization and will completely replace chemical fuel engines in 10–20 years.

This new development is a result of a scientific discovery and a technical invention that we have made recently.

Both from a scientific point of view and as a need to discover new sources of essential resources, exploring beyond our own planet is one of the remaining great missions for humanity. However, this is not without challenges, and as we look beyond the Moon to larger, more distant bodies, those challenges have become roadblocks to progress.

Whether used in the atmosphere or space, the chemical fuel rocket propulsion that has taken us this far has reached its practical limits. In terms of the thrust that can be generated, the speeds possible and the fuel needed, existing technology is something that must be worked around, rather than a driving force to achieve new goals. Even with technological

breakthroughs such as fusion reactors, the jet engine-powered craft will struggle to exceed even 50 km/sec speeds, while lifting capacity will remain severely limited too, presenting limiting performance on any future plans using the outdated propulsion systems that produce thrust by expelling reaction mass i.e., burned fuel shot backwards to provide acceleration.

Our current technology is only viable for manned flights to the moon and Mars, and even then, with significant compromises in how much equipment and how many people can be transported at once. But we should already be planning for longer journeys, reaching asteroids for the minerals they offer, new planets for the possibilities of settlements and more. Even travel between countries remains a barrier to trade, with flights being both expensive and a little faster than they were half a century ago, with severe limitations on the weights that can be realistically transported.

As we seek to push further away from our planet, speed becomes more than a hindrance, but instead is the thing that defines what we can do as humans. Distances become so vast, so quickly, that time taken to travel to bodies within our solar system, or further afield, dictates the kind of missions that can be attempted, and the kind of vehicles needed to accomplish them. Without a dramatic change in the speeds possible for our spacecraft, even the nearest stars become not a journey of exploration, but an impossible dream. With the human body having physical problems after 2 years in a weightless environment and deadly space radiation, travel beyond that remains impractical. Currently, that means no further than Mars. If we want to go further, and eventually we must go further, then we must travel faster. Much faster.

It is imperative then that our technology keeps up with the needs of not just space exploration, but the world around us. Providing fast, cheap transport around the globe can bring about a sea-change in how we live, boosting the life experience of every human being on the planet. The question has long been what kind of engine will drive this change, and we

are proud to say that having taken the first steps into this new world, the answer is Quantum Propulsion Systems.

Method: Quantum Bubble Propulsion–More Than A Theory

The idea behind quantum propulsion or electromagnetic propulsion has been around for a while, clean, cheap and very fast, it has been the panacea for a modern propulsion system both in the atmosphere and out in space. But recent research has brought that idea much closer to reality, with the discovery of the physical principles of the quantum vacuum cocoon motion, often referred to as the quantum bubble propulsion. Its full name is *Hyper-Relativistic Local-Dynamic Space Motion*. This concept was originally suggested by Albert Einstein, although there have been several detailed works about this space travel method since. Initially, in 1994, *The Warp Drive: Hyper-fast Travel Within General Relativity* [1] was a groundbreaking work on the subject by quantum physicist Miguel Alcubierre, and this has been built on in recent years, notably by *Hyper-fast positive energy warp drives*, by Lentz [2], *Physics of Field Propulsion: Outline of Quantum Field Theory and Its Applications for Space Propulsion* by Bobrick and Martire [3] published in 2018–2023 and some others.

The most groundbreaking work on the subject is the theoretical research and practical analysis of proposed interstellar travel methods undertaken by Mario J. Pinheiro and Takaaki Musha, world-renowned leaders in the field, and their seminal work *Physics of Field Propulsion: Outline of Quantum Field Theory and Its Applications for Space Propulsion* [4]. In the last couple of years, Mario J. Pinheiro has continued to build on this incredible research, with *New Framework to Study Electromagnetic Turbulence* [5], *Advanced Topics in Contemporary Physics for Engineering: Nanophysics, Plasma Physics, and Electrodynamics* [6] and finally *Advances in Engine Efficiency: Nanomaterials, Surface Engineering, and Quantum-based Propulsion* [7] all taking the idea of practical applications of quantum propulsion further than ever before.

The practical method for forming a quantum vacuum cocoon involves manipulating and controlling the physical mass of an object. This ability

allows us to approach Albert Einstein's famous equation, which illustrates the equivalence between mass and energy, from a different perspective. The equation is as follows:

$$E=mc^2$$

This equation leads to a function indicating that the faster we travel, the more energy is required for acceleration in our pursuit of reaching the speed of light. While it suggests that getting very close to the speed of light is possible with a fantastically tremendous amount of fuel, achieving the actual speed of light remains unattainable. As we approach the speed of light, the mass and kinetic energy of the vehicle increase, demanding more and more fuel for further acceleration (see Fig. 1):

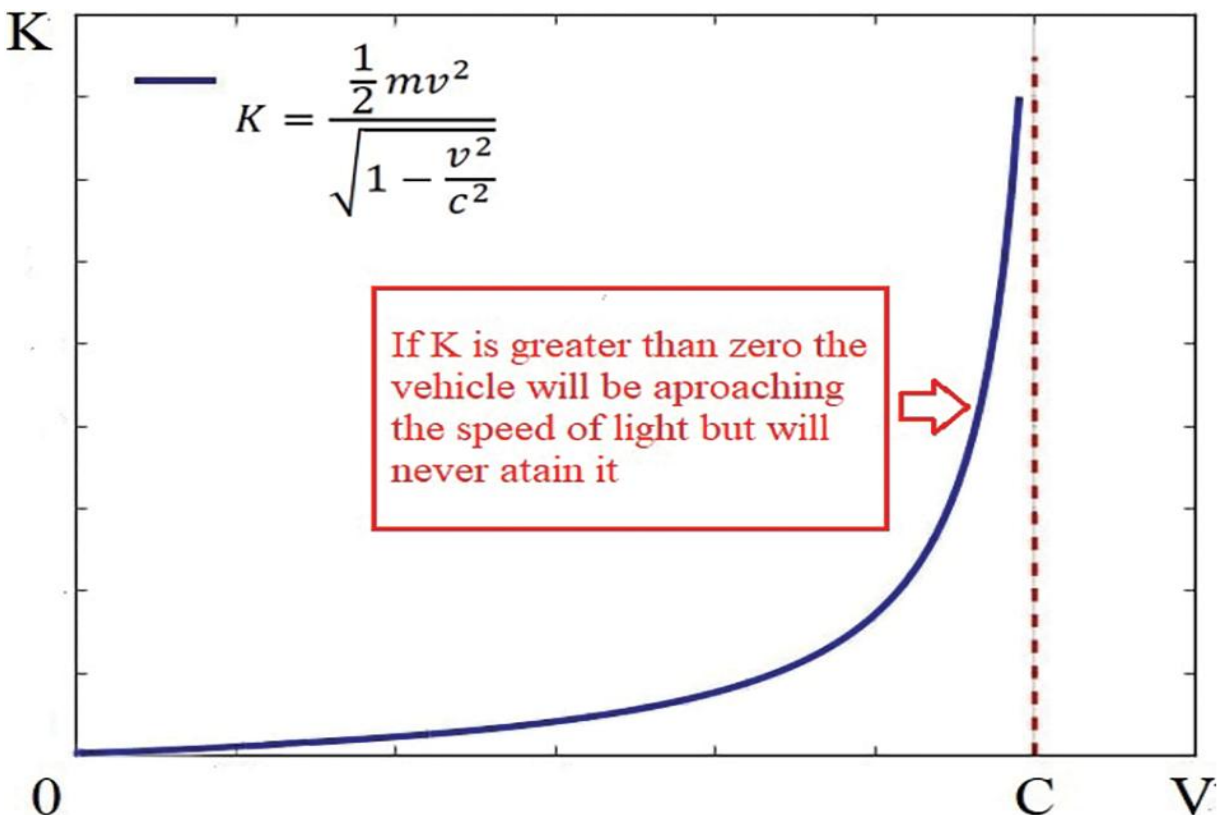


Fig. 1.Conventional spacecraft: K is a positive value.

$$K = \frac{1}{2}mv^2 \sqrt{1 - \frac{v^2}{c^2}}$$

where

c—speed of light,

v —speed of the vehicle,

m —mass of the vehicle,

K —kinetic energy of the vehicle.

However, everything changes when we gain control over the vehicle's mass, keeping it at zero point. This implies the ability to maintain the kinetic energy of the vehicle at zero point as well. Consequently, we can accelerate the vehicle to the speed of light instantly with minimal applied energy. This control allows us to reach any required speeds, surpassing the speed of light thousands of times, and to bring the vehicle to a standstill at will without significant energy input. Thus, spacecraft equipped with quantum propulsion systems will be capable of bypassing thousands of light-year distances in a few minutes (see Fig. 2). Here is the same equation where $m = 0$:

$$K = \frac{1}{2}mv^2 = 0$$

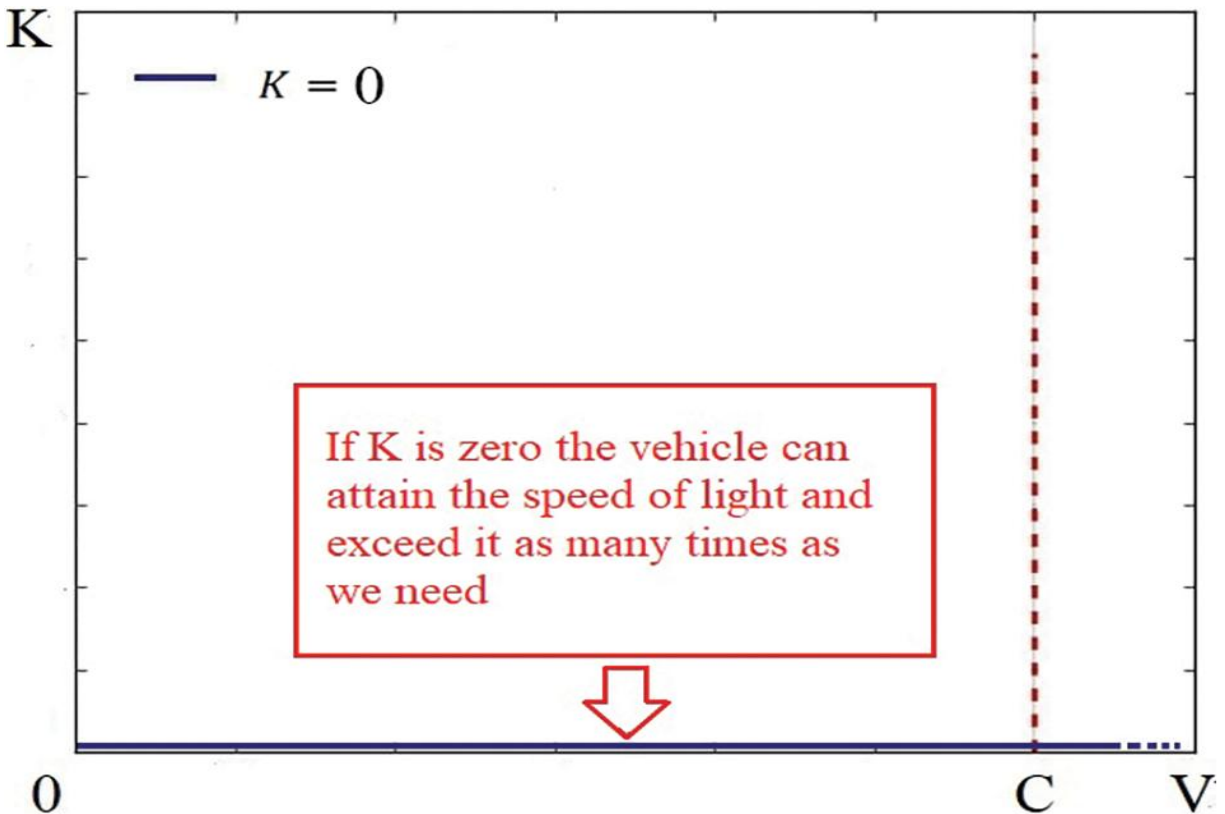


Fig. 2. Quantum vacuum cocoon-protected vehicle: K is zero.

Therefore, mastery over the mass of space vehicles grants us the capability to fully control the spacecraft's space-time motion, paving the way for unrestricted interstellar travel.

The Concept of Hyper-Relativistic Local-Dynamic Space Motion, or Quantum Propulsion

With so much research moving this concept forward rapidly, it is important to understand the theory and how that translates into a practical, effective solution for motive power. The basic operating principle of any quantum propulsion system is the generation of a quantum vacuum cocoon, or a quantum bubble, around a vehicle. This quantum cocoon dissolves any quantum connections between physical particles and fields around the vehicle and thus isolates this vehicle from the influence and resistance of the outside physical environment and physical fields. It forms a sphere of absolute vacuum around the vehicle where no material object of field can exist and function in its normal form.

The result is a vehicle with no theoretical speed limitations at all, and maneuverability on a scale never seen. The nature of the quantum bubble means that this doesn't just fly in space but could just as easily be used for atmosphere flight. Aerospace vehicles with no speed limits and incredible cost-efficiency make it possible to travel thousands of miles in a few seconds. You can begin to see the potential for transforming our entire way of life, not just space travel. But perhaps the most remarkable thing about quantum propulsion is that while it sounds like something straight off the pages of a sci-fi novel, it is something that already exists in nature. Many flying insects and spiders have been using their own internal electromagnetic mechanism to achieve the same concept almost since life first began on Earth, and still do today.

So, like the early attempts at flight using principles that mimicked birds' aerodynamics, our journey to quantum propulsion is grounded in reverse engineering nature, and a better understanding of how insects produce and harness their own quantum cocoon. Analysis shows that insects today use a combination of propulsion methods, using more traditional aerodynamic

flight modes for take-off, landing and hovering above flowers, switching to the quantum mode for rapid progress parallel to the ground or when hovering in readiness for fast movement, such as if they sense any kind of danger or preparing for acceleration to their cruising speed.

Insects generate their electromagnetic cocoon through a difference in electrical potential between the body and rapidly vibrating wings. That cocoon is strong enough to disrupt quantum connections, forces and quantum fields in the immediate space around the insects allowing them to glide in the electromagnetic field ignoring dynamic air resistance, gravitation influence and possible dust particle impacts. In some cases, such as spiders, the cocoon is created by increasing the electrical potential extended from their body antenna, relying on interaction with Earth's electromagnetic field to move. Some spiders can travel thousands of miles using this passive method.

Our team is the first group of engineers on the planet that have recreated this effect by means of electromechanical devices and holds IP for this invention. We are currently working on the development of the flight control system, aiming to build reliable and effective aerospace propulsion systems and vehicles. Through these experiments in replicating the quantum cocoon and unleashing the potential of rapid transit as a result, we believe that we have unlocked the true nature of matter and mass. Our experiments show that it is the combination of black matter and black energy that forms the foundation of the universe, with visible matter and its electromagnetic and gravitational fields at the top, alongside some yet unknown fields. All those fields and energies are interacting and displaying significant interdependence.

Every material object is formed of quantum particles that in their turn are formed by high-frequency oscillations of various known and unknown physical fields. Hence, oscillations form matter and its quantum gravitational fields that also form gravitational connections between objects and inside of these objects, thus shaping the main substance of the matter that we perceive as the tangible material objects being discussed. If we then try to move and accelerate these objects, whatever they may

be, we experience natural resistance or friction between the static universal fields and the net of quantum connections inside of the accelerating objects, forming an initial resistance to the movement called inertia that represents the main attribute of mass. That resistance is how we define mass and as we propose to understand it today.

To look at these processes differently, think of the mass as quantum windage, the quantum gravity connections and other fields as the sail that resists the air, while the combination of universal static fields forms the air that resists or compels movement. In our experiments with quantum cocoons, our generator emits an unknown until now form of energy that we have decided to call Q-Force. This Q-Force disturbs or completely eliminates oscillations of the physical fields, temporarily dissolving matter and its quantum connections around the Q-force generator and the flying machine, making it “invisible” to the surrounding matter and fields themselves, extinguishing quantum windage resistance, thus eliminating inertia effect and as a result the mass of the generator and the vehicle that it’s propelling.

The outcome of this is unlimited, frictionless movement in any direction and at any speed, including luminous and super-luminous speeds. Any vehicle using this system can be accelerated rapidly, then brought to a standstill immediately ignoring inertia and resulting G-forces, all requiring minimal energy to be applied to instigate and stop the movement. We have decided to express Q-Force as a percentage, for instance, a quantum generator that produces 80% of Q-Force will eliminate 80% of the mass and air resistance around the space vehicle, and so on. Of course, a 100% Q-Force renders any vehicle immune to surrounding matter and completely “switches off” its mass, so it becomes totally unaffected by any gravitational fields and momentum forces.

That 100% Q-Force is what we consider to be the perfect quantum bubble or cocoon, creating its own dimension within the bubble, separate yet within our own dimension. Inside this cocoon, the vehicle is unmoving, and completely static, when force is applied, it is the cocoon itself that moves. The vehicle is static within its own dimensional bubble, even

when the bubble itself moves within our dimension. Occupants of the vehicle inside that cocoon are therefore not subject to the acceleration and movement forces we expect, as in their cocoon, they remain entirely static.

It is this phenomenon that makes quantum propulsion so important for not just space travel, but rapid transportation of all kinds. Unlike some aerospace companies that are looking for ways to fight or eliminate gravity, we are approaching the issue of electromagnetic propulsion from the opposite side. We are not trying to eliminate gravity, instead, the Q-force generator is eliminating the mass of the spacecraft, thus making it “invisible” to gravity and any other physical fields and forces. That is the ultimate solution to the problem of rapid, safe and efficient travel to cope with our future needs, whether that is transportation between planets and star systems or across continents on Earth. We propose to call this definition of mass the Quantum Windage Theory, and alongside our continuing work on the application of these concepts, we are also seeking to initiate a robust scientific debate about the Quantum Windage concept and the possibilities it offers for the development of new technologies.

This is an accelerating conventional spacecraft that, like any other material object, is fighting its own mass inertia burning tons of chemical fuel (see [Fig. 3](#)). This resistance, which we call inertia, is the result of friction between quantum particles and their gravitational interconnections of the object’s own body and the static energy fields of the universe. The physical phenomena, which we call mass is nothing more than this friction or “quantum windage” as we proposed to call it. If we manage to eliminate this friction, i.e., inertia, we effectively make the mass of the object unrecognisable by the surrounding matter and fields resulting in absolute freedom of speed and manoeuvre (see [Fig. 4](#)).

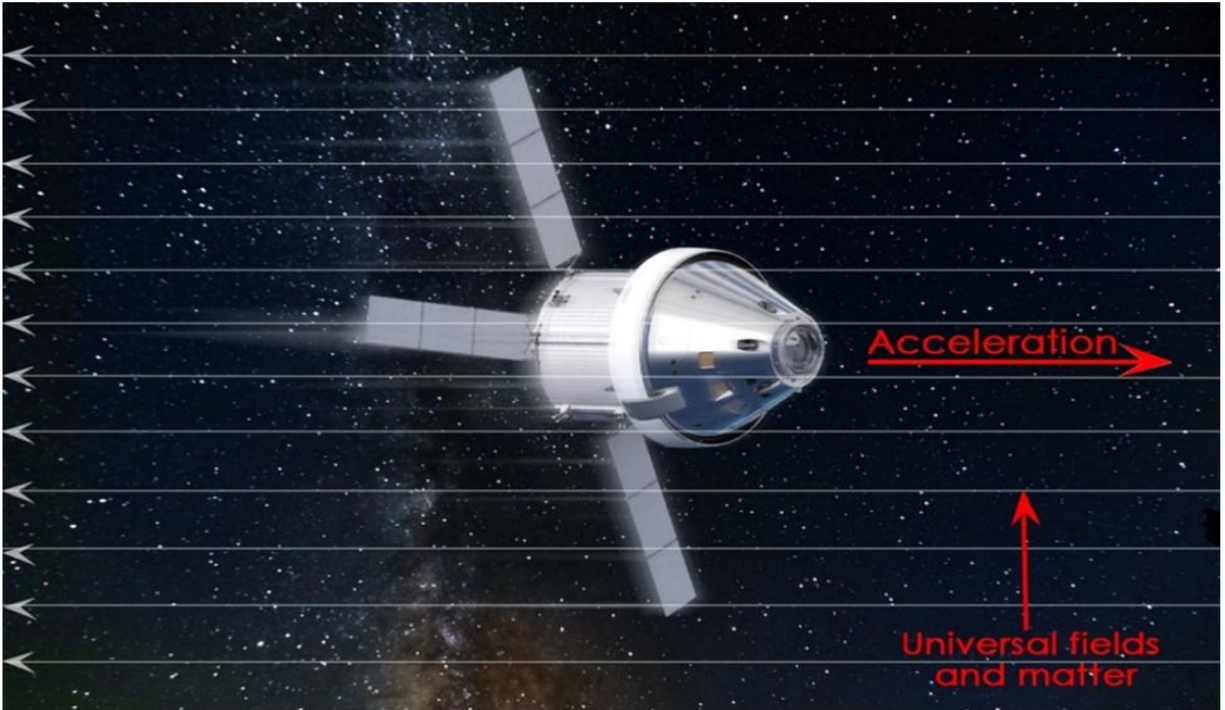


Fig. 3.Conventional spacecraft.

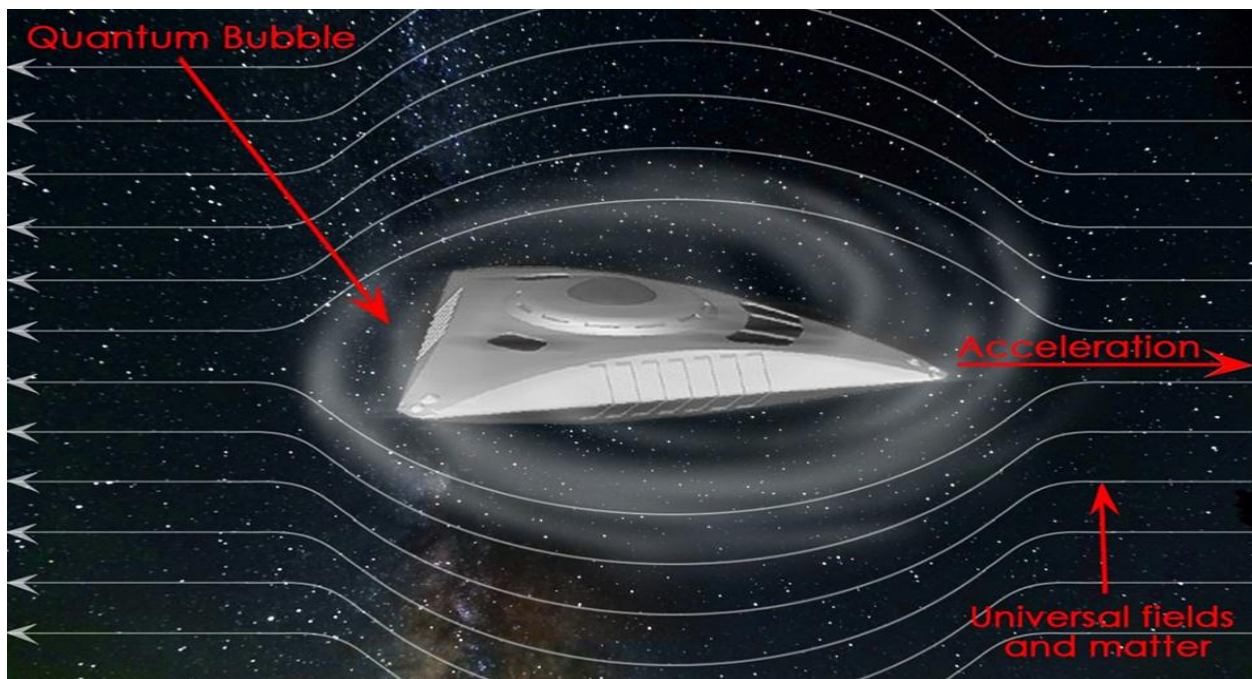


Fig. 4.Quantum propulsion system powered spacecraft flight–no quantum friction, no inertia effect.

Thus, when the quantum generator of the propulsion system is on and at 100% power (see Fig. 5), the space vehicle glides via the energy-free tunnel, forming it by generating a quantum vacuum bubble around itself that conveniently isolates the vehicle from the surrounding chemical environment and combination of universal energy fields (see Fig. 6). If we apply a controlling impulse to one side of the bubble, we will effortlessly accelerate the bubble and the vehicle inside the bubble to any speed including speed of light. Thus, electromagnetic impulses of predefined frequency and configuration will provide these vehicles with propulsive and flight control momentum.

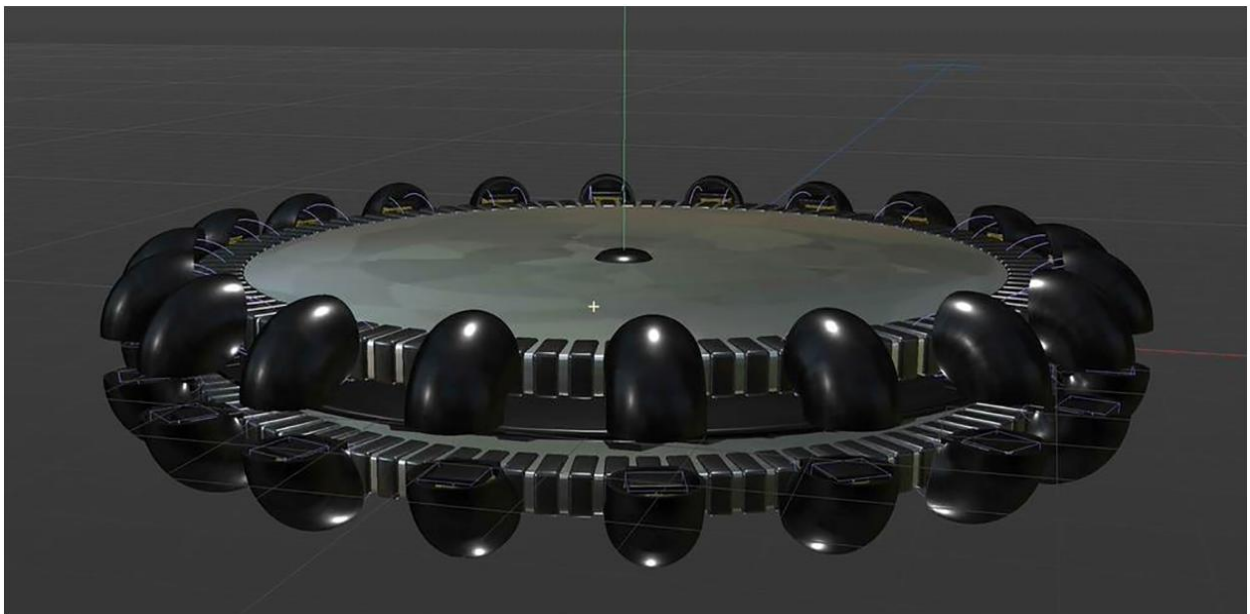


Fig. 5.The main core of quantum propulsion system: Q-force generator (holding frame, piping and cabling not shown).

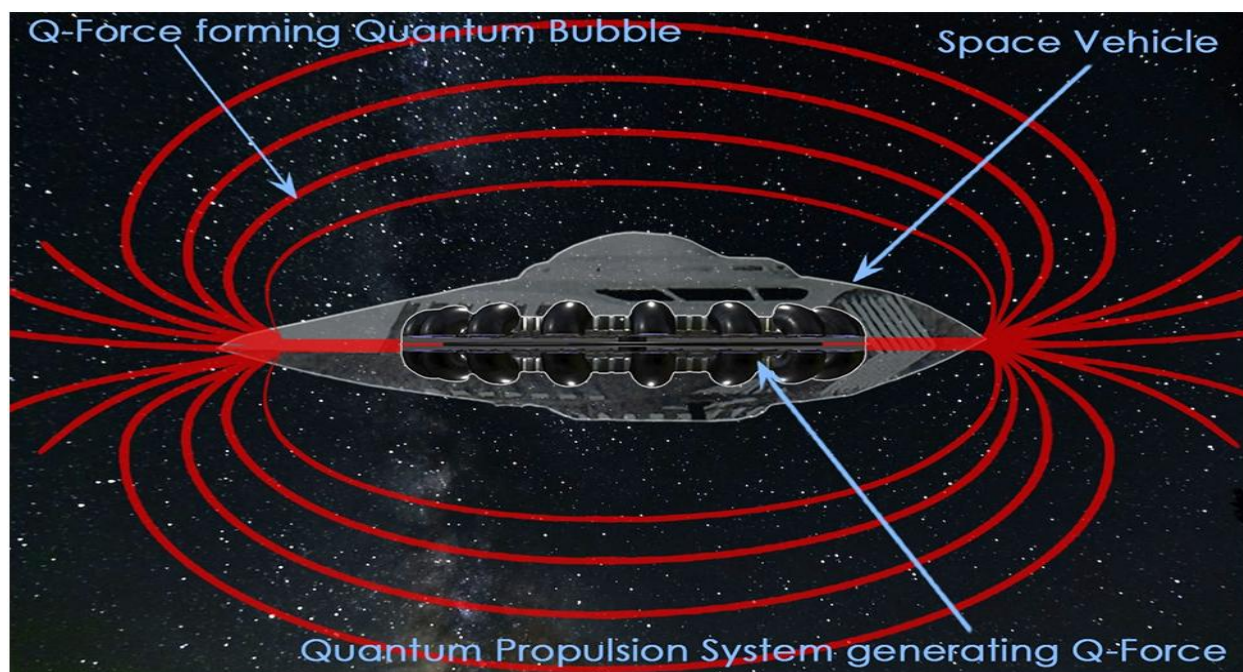


Fig. 6. Quantum propulsion system generates a Q-force field around the spacecraft forming two safe half-spheres around the vehicle and inside of the bubble, the physical properties of matter and fields inside of those half-spheres remain undisturbed.

Our Roadmap to Quantum Propulsion

Our research and development are continuing under the business identity trademarks of Quantum Propulsion Technologies Ltd., operating both short- and long-term programs that aim to deliver real-world applications of the concept. This begins with the design, development and testing of the first workable and fully operational quantum propulsion system-propelled prototype within the next two to three years. This initial prototype will operate as proof of concept, demonstrating the many advantages of quantum propulsion systems for both our potential investors and our potential customers alike.

Once the first fully operational vehicles have been built, that proof of concept will be further developed into a commercially viable high-speed and highly maneuverable drone. With potential use applications including surveying and any other visual observation (including military and law enforcement intel gathering) or as a highly efficient and fast weapon

delivery platform, this initial product should see high demand and deliver funding to move towards our longer-term goals.

Building on those initial drone applications, more advanced versions could be used to launch satellites into LEO, dramatically reducing costs for any space launch, but the ability to carry higher loads at almost any speed would also make them eminently suitable for deep space exploration. Delivering sets of scientific instruments and surveying planets, asteroids and more, these drones could be the vanguard in our full-scale exploration of our solar system planets, as well as in scouting asteroids for much-needed minerals.

Beyond our initial 5-year development cycle, Quantum Propulsion Ltd. expects to develop more tailored vehicles to suit business needs. We expect the first of these to be a four-seater manned spacecraft that we will design, develop and launch within a decade. These vehicles could be used for scientific interplanetary space exploration, space tourism, Astro-geological surveys, experimental small-scale asteroid mining operations within our solar system and as a basis for building various types of versatile military aerospace vehicles.

Continually moving forward, these first small, manned craft will pave the way for larger space vehicles offering high-capacity transport spaceships that will be capable of supporting industrial-scale commercial space mining operations and the construction of planetary bases within our solar system. Lessons learned during these developments will lead on to the ultimate goal of these projects, large interstellar transport spaceships that could be used for the exploration of distant planetary systems and colonization of habitable planets, with the first prototypes appearing within twenty years.

Quantum Propulsion as Part of a New Human Culture

Alongside Quantum Propulsion Ltd. we also operate Intstelforce Ltd., which is tasked with placing these technological advancements within our society and ensuring that these dramatic changes in capability translate into tangible benefits for all. Intstelforce Ltd. will act as an initiator of all

future space mining and space colonization projects, including habitable planets colonization as the technology progresses.

Currently, we have launched our New Earth Project under the Intstelforce Ltd. umbrella. This project sets out to create an international think tank, uniting young people looking to create a new, politically independent, planet-state on the surface of one of the habitable planets that quantum propulsion will put within our reach. The prime task of the New Earth project group is to devise the most appropriate and efficient methods of scouting for new planets suitable for habitation. That includes consideration of various aspects of this venture such as climatic, tectonic and biological conditions, and drawing up appropriate plans for the colonization process. This includes ideas about the economic and political organization of the new planet-states and the most efficient ways of governing them. While this may seem a little advanced, it is important to remember that once quantum propulsion is achieved, the speed of colonisation will be extremely rapid. Our large transportation spacecraft will be capable of transporting hundreds of thousands of people to the other planetary systems and issues like governance and sustaining of new worlds and communities must be in place and ready to go.

Results: Quantum Propulsion in Practice, What can we Expect?

Like all new technologies, and especially those that offer a breakthrough in how we understand and interact with the world around us, quantum propulsion sounds both exciting and wonderful. But it is not the technology itself that really matters in the end, but in what that technology does for our lives. For instance, television broadcasts are not amazing because of the physics behind how data is transmitted and turned into moving images, but that it changed the way the entire world consumes entertainment and information. Television changed the way we live, and the crucial thing about quantum propulsion is that it will do the same.

Before looking at the wider impact, it is important to go through the very clear advantages of quantum propulsion systems and why they offer such a leap in capability compared to the current reliance on chemical fuel engines.

1. **Unlimited Speed:** Theoretically it is possible to achieve the speed of light from the outset, and potentially master superluminal warp drive motion speeds, making these vehicles perfectly suitable for feasible interstellar superluminal travel and the nearest planetary systems exploration.
2. **Highly Maneuverable:** Rapid acceleration and sharp-angle changes in direction are possible as neither the vehicle nor crew are subject to any kind of inertia influence and G-force within the quantum cocoon.
3. **100% Crew Protection:** Because the vehicle and crew sit within their own quantum cocoon, in effect in a separate dimension to the world around them, they are isolated from any kind of radiation encountered in space. In addition, because of their enormous lifting capacity, these vehicles can be constructed with heavy metallic armor that will be able to protect the crew against this radiation when the propulsion system is off (while on the surfaces on the celestial bodies that don't have any atmosphere for example), with no penalty for movement or energy use.
4. **Enormous Load Capacity:** Within the quantum cocoon the vehicle and its contents are in effect zero weight while the system is active. As a result, the load capacity of the vehicle is restricted only by its cargo bay size.
5. **Zero Aerodynamic and Hydrodynamic Resistance:** Vehicles equipped with quantum propulsion systems can fly at any speed ignoring atmospheric and water resistance, ignoring space particles and other destructive impacts and interstellar gas cloud abrasion that could risk alternative solutions.
6. **Highly Efficient:** Without the need for rocket boosters or large amounts of reaction mass i.e., propelling substances for expulsion, a quantum powered space vehicle will be able to accelerate from the Earth surface directly into the open space and to attain any speed at will. These vehicles don't require any chemical fuel or any other waste products. These propulsion systems don't emit anything, they are 100% green and environmentally friendly. Q-force generator can be powered by ferromagnets that could be replaced or recharged

once in 3–5 years. There is also no need for huge numbers of personnel to oversee any flight, the vehicles are going to be mechanically simple and completely autonomous, with the flight preparations and the ground control no more complex than flight preparations and control of a small private jet plane or helicopter. This also means there is no need for expensive runways and spaceports thanks to the 100% VTOL capability of these craft.

7. **Extremely Cost Effective:** Dramatically lower production costs compared to chemical fuel space vehicles, which allows significantly lower price per kilo space launch ratio. The manufacturing and maintenance of vehicles equipped with quantum propulsion systems will be no more expensive than manufacturing of jet planes or helicopters of the same size (see [Fig. 7](#)). Building a combination of Orion NASA spacecraft with SLS costs more than 4 billion USD. They both are expendable vehicles, and they can be used just once. Building reusable QPS-equipped spacecraft will cost just about 500–600 million USD and it will be capable of performing 200–300 flights before any major refurbishment. The difference is absolutely staggering.

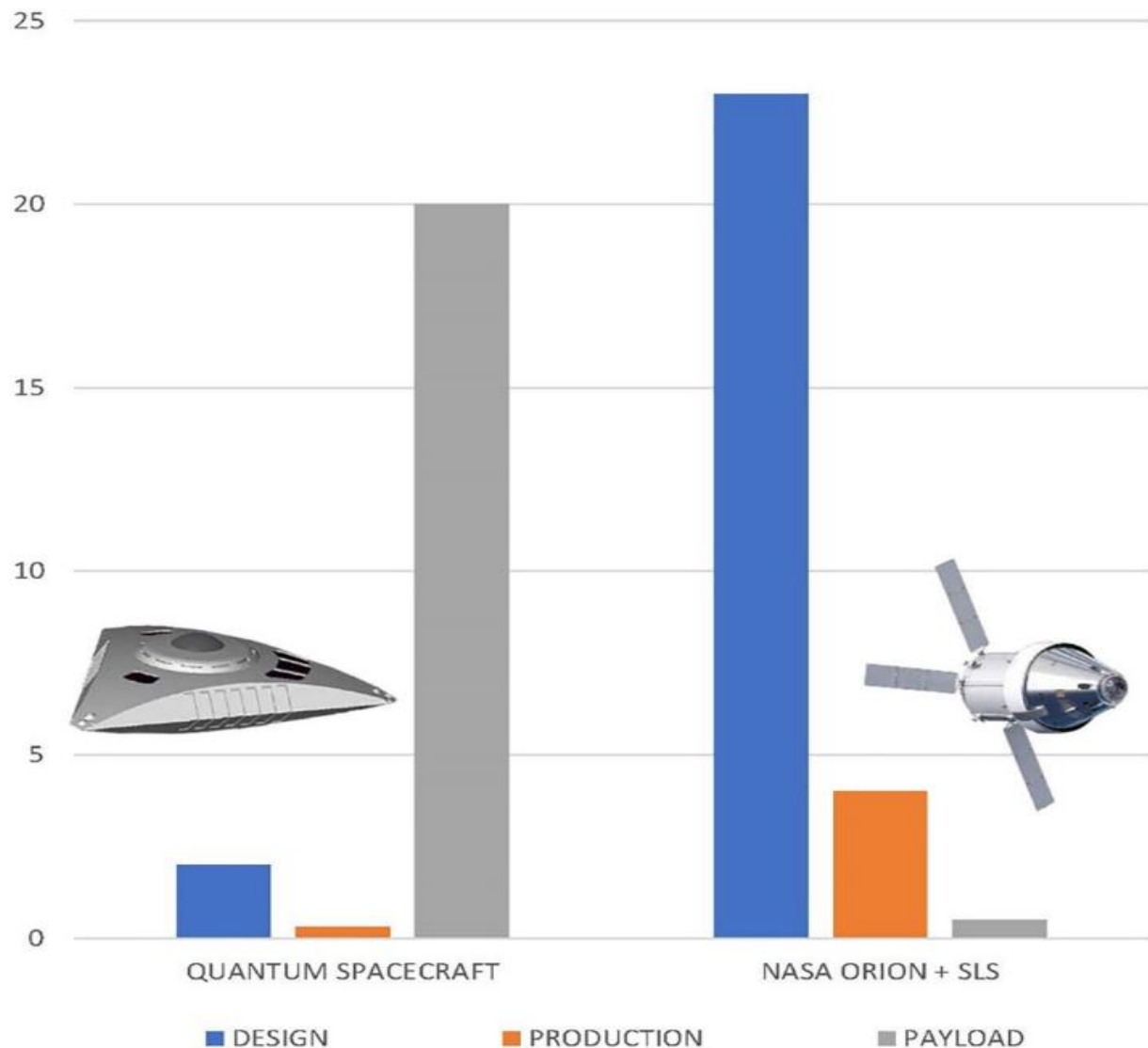


Fig. 7. Orion + SLS spacecraft combination and QPS spacecraft cost comparison in billions USD (Moon exploration configuration).

Putting Quantum Propulsion into Practice

When developing this new system, the goal is to deliver a mature, functional solution that has practical applications. In terms of commercial uses, there are several options here. Primarily, the quantum propulsion system will unlock the opportunity for asteroid and interplanetary mining, allowing access to resources for human development in a way that does not harm our planet and home. As we deplete resources on Earth, this is

perhaps the only option to maintain the society and way of life we have created, and as such is crucial for the future of the entire human race.

Currently, scientists believe that it is impractical and commercially unviable to use traditional rocket-propelled vehicles for this type of mining. Prohibiting cost, travel times and the lack of load capacity mean that space mining by means of conventional rocket engine-propelled spacecraft is not commercially feasible. It seems then, that quantum propulsion is the only viable option for providing society with the natural resources it needs. This kind of mining will have a huge effect throughout the world too, as it dramatically shifts resource prices downwards, helping poorer communities and ensuring that everyone can have the things they need for a good quality of life.

However, while the importance of such initiatives cannot be overstated, there are other applications that will have a significant effect on the way we live too. The speed and unprecedented maneuverability of a vehicle contained within a quantum cocoon make them incredibly valuable for military applications. Combined with AI control you can have aircraft that are much faster, more agile and carry much heavier weapon payloads, all in a single craft. They could perform maneuvers that would be physically impossible for a conventional aircraft due to immunity to G-Forces and would be superior to any fighter plane operating on the planet.

Further space exploration requires large, fast vehicles, and quantum propulsion is the key to creating spacecraft fast enough to reach any planets in our solar system, and eventually other stars, in timescales that are survivable for its crew. This exploration will transform the way we see the universe around us, opening up new opportunities for settling on other planets, creating new independent planet-states, and creating interplanetary corporations and markets.

But it is not just in space where the changes made possible by quantum propulsion will manifest. Imagine a world where a flight from London to Sydney or LA takes less than half an hour and is cheaper than your taxi fare to the airport right now. Shrinking the world in this way, and making easy travel, anywhere, accessible to all, will be the spark for the next

industrial revolution. Incomes will be boosted for all as new opportunities become available, and we can focus on value, rather than securing our share limited by the size of the planet's resources. It is transformational technology in every way, unleashing a tidal wave of potential both on Earth and in space.

Conclusion

In the same way that steam power transformed our world in the first industrial revolution, quantum power will push the next. We will live in a world where anywhere is just a few minutes' journey away, and that journey is affordable for all, not locked behind a barrier that only the richest can afford. People will be able to easily commute anywhere, maximizing their skills and knowledge, boosting careers and opening new opportunities to all, regardless of where they are born.

But it will also do so much more, bringing other planets, asteroid resources and even other star systems within reach. Humanity will be limited only by our imagination and will to explore, and it all began with an insect, an idea and our passion for technology.

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Zero-point energy

Zero-point energy (ZPE) is the lowest possible [energy](#) that a [quantum mechanical](#) system may have. Unlike in [classical mechanics](#), quantum systems constantly [fluctuate](#) in their lowest energy state as described by the [Heisenberg uncertainty principle](#).^[1] Therefore, even at [absolute zero](#), atoms and molecules retain some vibrational motion. Apart from [atoms](#) and [molecules](#), the empty space of [the vacuum](#) also has these properties. According to [quantum field theory](#), the universe can be thought of not as isolated particles but continuous fluctuating [fields](#): [matter fields](#), whose [quanta](#) are [fermions](#) (i.e., [leptons](#) and [quarks](#)), and [force fields](#), whose quanta are [bosons](#) (e.g., [photons](#) and [gluons](#)). All these fields have zero-point energy.^[2] These fluctuating zero-point fields lead to a kind of reintroduction of an [aether](#) in physics^{[1][3]} since some systems can detect the existence of this energy.^[citation needed] However, this aether cannot be thought of as a physical medium if it is to be [Lorentz invariant](#) such that there is no contradiction with [Einstein's](#) theory of [special relativity](#).^[1]

The notion of a zero-point energy is also important for [cosmology](#), and physics currently lacks a full theoretical model for understanding zero-point energy in this context; in particular, the discrepancy between theorized and observed vacuum energy in the universe is a source of major contention.^[4] Yet according to Einstein's theory of [general relativity](#), any such energy would gravitate, and the experimental evidence from the [expansion of the universe](#), [dark energy](#) and the [Casimir effect](#) shows any such energy to be exceptionally weak. One proposal that attempts to address this issue is to say that the [fermion field](#) has a negative zero-point energy, while the [boson field](#) has positive zero-point energy and thus these energies somehow cancel out each other.^{[5][6]} This idea would be true if [supersymmetry](#) were an exact [symmetry of nature](#); however, the [Large Hadron Collider](#) at [CERN](#) has so far found no evidence to support it. Moreover, it is known that if supersymmetry is valid at all, it is at most a [broken symmetry](#), only true at very high energies, and no one has been able to show a theory where zero-point cancellations occur in the low-energy universe we observe today.^[6] This discrepancy is known as the [cosmological constant problem](#) and it is one of the greatest [unsolved mysteries in physics](#). Many physicists believe that "the vacuum holds the key to a full understanding of nature".^[7]

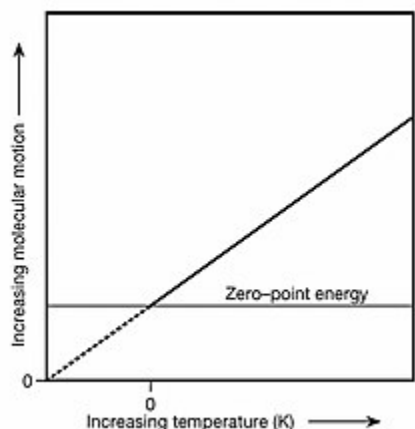
Etymology and terminology

[\[edit\]](#)

The term **zero-point energy (ZPE)** [is a translation](#) from the German ***Nullpunktenergie***.^[8] Sometimes used interchangeably with it are the terms **zero-point radiation** and **ground state energy**. The term **zero-point field (ZPF)** can be used when referring to a specific vacuum field, for instance the [QED vacuum](#) which specifically deals with [quantum electrodynamics](#) (e.g., electromagnetic interactions between photons, electrons and the vacuum) or the [QCD vacuum](#) which deals with [quantum chromodynamics](#) (e.g., [color charge](#) interactions between quarks, gluons and the vacuum). A vacuum can be viewed not as empty space but as the

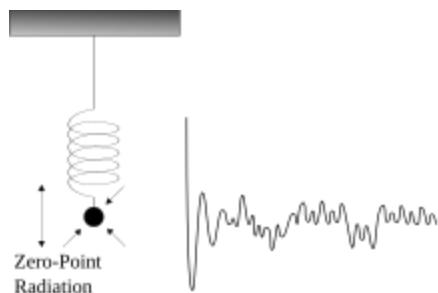
combination of all zero-point fields. In [quantum field theory](#) this combination of fields is called the vacuum state, its associated zero-point energy is called the [vacuum energy](#) and the average energy value is called the [vacuum expectation value](#) (VEV) also called its **condensate**.

Overview



Kinetic energy vs temperature

In [classical mechanics](#) all [particles](#) can be thought of as having some [energy](#) made up of their [potential energy](#) and [kinetic energy](#). [Temperature](#), for example, arises from the intensity of random particle motion caused by kinetic energy (known as [Brownian motion](#)). As temperature is reduced to [absolute zero](#), it might be thought that all motion ceases and particles come completely to rest. In fact, however, kinetic energy is retained by particles even at the lowest possible temperature. The random motion corresponding to this zero-point energy never vanishes; it is a consequence of the [uncertainty principle](#) of [quantum mechanics](#).^{[[citation needed](#)]}



Zero-point radiation continually imparts random impulses on an [electron](#), so that it never comes to a complete stop. Zero-point radiation gives the [oscillator](#) an average energy equal to the frequency of oscillation multiplied by one-half of the [Planck constant](#).

The uncertainty principle states that no object can ever have precise values of position and velocity simultaneously. The total energy of a quantum mechanical object (potential and kinetic) is described by its [Hamiltonian](#) which also describes the system as a harmonic oscillator, or [wave function](#), that fluctuates between various energy states (see [wave-particle duality](#)). All quantum mechanical systems undergo fluctuations even in their ground state, a consequence of their [wave](#)-like nature. The uncertainty principle requires every quantum mechanical system to have a fluctuating zero-point energy

greater than the minimum of its classical [potential well](#). This results in motion even at absolute zero. For example, [liquid helium](#) does not freeze under atmospheric pressure regardless of temperature due to its zero-point energy.

Given the equivalence of mass and energy expressed by [Albert Einstein's](#) $E = mc^2$, any point in [space](#) that contains energy can be thought of as having mass to create particles. Modern physics has developed quantum field theory (QFT) to understand the fundamental interactions between matter and forces; it treats every single point of space as a [quantum harmonic oscillator](#). According to QFT the universe is made up of matter fields, whose quanta are [fermions](#) (i.e. [leptons](#) and [quarks](#)), and force fields, whose quanta are [bosons](#) (e.g. [photons](#) and [gluons](#)). All these fields have zero-point energy.^[2] Recent experiments support the idea that particles themselves can be thought of as excited states of the underlying [quantum vacuum](#), and that all properties of matter are merely vacuum fluctuations arising from interactions of the zero-point field.^[9]

The idea that "empty" space can have an intrinsic energy associated with it, and that there is no such thing as a "true vacuum" is seemingly unintuitive. It is often argued that the entire universe is completely bathed in the zero-point radiation, and as such it can add only some constant amount to calculations. Physical measurements will therefore reveal only deviations from this value.^[10] For many practical calculations zero-point energy is dismissed by fiat in the mathematical model as a term that has no physical effect. Such treatment causes problems however, as in Einstein's theory of [general relativity](#) the absolute energy value of space is not an arbitrary constant and gives rise to the [cosmological constant](#). For decades most physicists assumed that there was some undiscovered fundamental principle that will remove the infinite zero-point energy and make it completely vanish. If the vacuum has no intrinsic, absolute value of energy it will not gravitate. It was believed that as the universe expands from the aftermath of the [Big Bang](#), the energy contained in any unit of empty space will decrease as the total energy spreads out to fill the volume of the universe; [galaxies](#) and all matter in the universe should begin to decelerate. This possibility was ruled out in 1998 by the discovery that the expansion of the universe is not slowing down but is in fact accelerating, meaning empty space does indeed have some intrinsic energy. The discovery of [dark energy](#) is best explained by zero-point energy, though it still remains a mystery as to why the value appears to be so small compared to the huge value obtained through theory – the [cosmological constant problem](#).^[5]

Many physical effects attributed to zero-point energy have been experimentally verified, such as [spontaneous emission](#), [Casimir force](#), [Lamb shift](#), [magnetic moment of the electron](#) and [Delbrück scattering](#).^{[11][12]} These effects are usually called "radiative corrections".^[13] In more complex nonlinear theories (e.g. QCD) zero-point energy can give rise to a variety of complex phenomena such as [multiple stable states](#), [symmetry breaking](#), [chaos](#) and [emergence](#). Active areas of research include the effects of virtual particles,^[14] [quantum entanglement](#),^[15] the difference (if any) between [inertial and gravitational mass](#),^[16] variation in the [speed of light](#),^[17] a reason for the observed value of the [cosmological constant](#)^[18] and the nature of dark energy.^{[19][20]}

History

Early aether theories



James Clerk Maxwell

Zero-point energy evolved from historical ideas about the [vacuum](#). To [Aristotle](#) the vacuum was τὸ κενόν, "the empty"; i.e., space independent of body. He believed this concept violated basic physical principles and asserted that [the elements](#) of [fire](#), [air](#), [earth](#), and [water](#) were not made of atoms, but were continuous. To the [atomists](#) the concept of emptiness had absolute character: it was the distinction between existence and nonexistence.^[21] Debate about the characteristics of the vacuum were largely confined to the realm of [philosophy](#), it was not until much later on with the beginning of [the renaissance](#), that [Otto von Guericke](#) invented the first vacuum pump and the first testable scientific ideas began to emerge. It was thought that a totally empty volume of space could be created by simply removing all gases. This was the first generally accepted concept of the vacuum.^[22]

Late in the 19th century, however, it became apparent that the evacuated region still contained [thermal radiation](#). The existence of the [aether](#) as a substitute for a true void was the most prevalent theory of the time. According to the successful [electromagnetic](#) aether theory based upon [Maxwell's electrodynamics](#), this all-encompassing aether was endowed with energy and hence very different from nothingness. The fact that electromagnetic and gravitational phenomena were transmitted in empty space was considered evidence that their associated aethers were part of the fabric of space itself. However Maxwell noted that for the most part these aethers were *ad hoc*:

To those who maintained the existence of a plenum as a philosophical principle, nature's abhorrence of a vacuum was a sufficient reason for imagining an all-surrounding aether ... 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, till a space had been filled three or four times with aethers.^[23]

Moreover, the results of the [Michelson–Morley experiment](#) in 1887 were the first strong evidence that the then-prevalent aether theories were seriously flawed, and initiated a line of research that eventually led to [special relativity](#), which ruled out the idea of a

stationary aether altogether. To scientists of the period, it seemed that a true vacuum in space might be created by cooling and thus eliminating all radiation or energy. From this idea evolved the second concept of achieving a real vacuum: cool a region of space down to absolute zero temperature after evacuation. Absolute zero was technically impossible to achieve in the 19th century, so the debate remained unsolved.

Second quantum theory



Planck in 1918, the year he received the [Nobel Prize in Physics](#) for his work on [quantum theory](#)

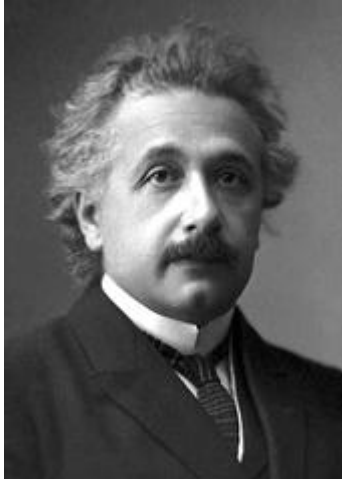
In 1900, [Max Planck](#) derived the average energy ε of a single *energy radiator*, e.g., a

vibrating atomic unit, as a function of absolute temperature:^[24] where h is the [Planck constant](#), ν is the [frequency](#), k is the [Boltzmann constant](#), and T is the absolute [temperature](#). The zero-point energy makes no contribution to Planck's original law, as its existence was unknown to Planck in 1900.^[25]

The concept of zero-point energy was developed by [Max Planck](#) in Germany in 1911 as a corrective term added to a zero-grounded formula developed in his original quantum theory in 1900.^[26]

In 1912, Max Planck published the first journal article to describe the discontinuous emission of radiation, based on the discrete quanta of energy.^[27] In Planck's "second quantum theory" resonators absorbed energy continuously, but emitted energy in discrete energy quanta only when they reached the boundaries of finite cells in phase space, where their energies became integer multiples of $h\nu$. This theory led Planck to his new radiation law, but in this version energy resonators possessed a zero-point energy, the smallest average energy a resonator could take on. Planck's radiation equation contained a residual energy factor, one $h\nu/2$, as an additional term dependent on the frequency ν , which was greater than zero (where h is the Planck constant). It is therefore widely agreed that "Planck's equation marked the birth of the concept of zero-point energy."^[28] In a series of papers from 1911 to 1913,^[29] Planck found the average

energy of an oscillator to be:^{[26][30]}



Einstein's official 1921 portrait after receiving the Nobel Prize in Physics

Soon, the idea of zero-point energy attracted the attention of Albert Einstein and his assistant [Otto Stern](#).^[31] In 1913 they published a paper that attempted to prove the existence of zero-point energy by calculating the [specific heat](#) of hydrogen gas and compared it with the experimental data. However, after assuming they had succeeded, they retracted support for the idea shortly after publication because they found Planck's second theory may not apply to their example. In a letter to [Paul Ehrenfest](#) of the same year Einstein declared zero-point energy "dead as a doornail".^[32] Zero-point energy was also invoked by [Peter Debye](#),^[33] who noted that zero-point energy of the atoms of a [crystal lattice](#) would cause a reduction in the intensity of the diffracted radiation in [X-ray diffraction](#) even as the temperature approached absolute zero. In 1916 [Walther Nernst](#) proposed that empty space was filled with zero-point [electromagnetic radiation](#).^[34] With the development of general relativity Einstein found the energy density of the vacuum to contribute towards a cosmological constant in order to obtain static solutions to his field equations; the idea that empty space, or the vacuum, could have some intrinsic energy associated with it had returned, with Einstein stating in 1920:

There is a weighty argument to be adduced in favour of the aether hypothesis. To deny the aether is ultimately to assume that empty space has no physical qualities whatever. The fundamental facts of mechanics do not harmonize with this view ... according to the general theory of relativity space is endowed with physical qualities; in this sense, therefore, there exists an aether. According to the general theory of relativity space without aether is unthinkable; for in such space there not only would be no propagation of light, but also no possibility of existence for standards of space and time (measuring-rods and clocks), nor therefore any space-time intervals in the physical sense. But this aether may not be thought of as endowed with the quality characteristic of ponderable media, as consisting of parts which may be tracked through time. The idea of motion may not be applied to it.^{[35][36]}



Heisenberg, 1924

Kurt Bennewitz [de] and Francis Simon (1923),^[37] who worked at Walther Nernst's laboratory in Berlin, studied the melting process of chemicals at low temperatures. Their calculations of the melting points of hydrogen, argon and mercury led them to conclude that the results provided evidence for a zero-point energy. Moreover, they suggested correctly, as was later verified by Simon (1934),^{[38][39]} that this quantity was responsible for the difficulty in solidifying helium even at absolute zero. In 1924 Robert Mulliken^[40] provided direct evidence for the zero-point energy of molecular vibrations by comparing the band spectrum of ^{10}BO and ^{11}BO : the isotopic difference in the transition frequencies between the ground vibrational states of two different electronic levels would vanish if there were no zero-point energy, in contrast to the observed spectra. Then just a year later in 1925,^[41] with the development of matrix mechanics in Werner Heisenberg's article "Quantum theoretical re-interpretation of kinematic and mechanical relations" the zero-point energy was derived from quantum mechanics.^[42]

In 1913 Niels Bohr had proposed what is now called the Bohr model of the atom,^{[43][44][45]} but despite this it remained a mystery as to why electrons do not fall into their nuclei. According to classical ideas, the fact that an accelerating charge loses energy by radiating implied that an electron should spiral into the nucleus and that atoms should not be stable. This problem of classical mechanics was nicely summarized by James Hopwood Jeans in 1915: "There would be a very real difficulty in supposing that the (force) law $1/r^2$ held down to the zero values of r . For the forces between two charges at zero distance would be infinite; we should have charges of opposite sign continually rushing together and, when once together, no force would tend to shrink into nothing or to diminish indefinitely in size."^[46] The resolution to this puzzle came in 1926 when Erwin Schrödinger introduced the Schrödinger equation.^[47] This equation explained the new, non-classical fact that an electron confined to be close to a nucleus would necessarily have a large kinetic energy so that the minimum total energy (kinetic plus potential) actually occurs at some positive separation rather than at zero separation; in other words, zero-point energy is essential for atomic stability.^[48]

Quantum field theory and beyond

In 1926, Pascual Jordan^[49] published the first attempt to quantize the electromagnetic field. In a joint paper with Max Born and Werner Heisenberg he considered the field inside a cavity as a superposition of quantum harmonic oscillators. In his calculation, he

found that in addition to the "thermal energy" of the oscillators there also had to exist an infinite zero-point energy term. He was able to obtain the same fluctuation formula that Einstein had obtained in 1909.^[50] However, Jordan did not think that his infinite zero-point energy term was "real", writing to Einstein that "it is just a quantity of the calculation having no direct physical meaning".^[51] Jordan found a way to get rid of the infinite term, publishing a joint work with Pauli in 1928,^[52] performing what has been called "the first infinite subtraction, or renormalisation, in quantum field theory".^[53]



Paul Dirac, 1933

Building on the work of Heisenberg and others, [Paul Dirac](#)'s theory of emission and absorption (1927)^[54] was the first application of the quantum theory of radiation. Dirac's work was seen as crucially important to the emerging field of quantum mechanics; it dealt directly with the process in which "particles" are actually created: [spontaneous emission](#).^[55] Dirac described the quantization of the [electromagnetic field](#) as an ensemble of [harmonic oscillators](#) with the introduction of the concept of [creation and annihilation operators](#) of particles. The theory showed that spontaneous emission depends upon the zero-point energy fluctuations of the electromagnetic field in order to get started.^{[56][57]} In a process in which a photon is annihilated (absorbed), the photon can be thought of as making a transition into the vacuum state. Similarly, when a photon is created (emitted), it is occasionally useful to imagine that the photon has made a transition out of the vacuum state. In the words of Dirac:^[54]

The light-quantum has the peculiarity that it apparently ceases to exist when it is in one of its stationary states, namely, the zero state, in which its momentum and therefore also its energy, are zero. When a light-quantum is absorbed it can be considered to jump into this zero state, and when one is emitted it can be considered to jump from the zero state to one in which it is physically in evidence, so that it appears to have been created. Since there is no limit to the number of light-quanta that may be created in this way, we must suppose that there are an infinite number of light quanta in the zero state ...

Contemporary physicists, when asked to give a physical explanation for spontaneous emission, generally invoke the zero-point energy of the electromagnetic field. This view was popularized by [Victor Weisskopf](#) who in 1935 wrote:^[58]

From quantum theory there follows the existence of so called zero-point oscillations; for example each oscillator in its lowest state is not completely at rest but always is moving about its equilibrium position. Therefore electromagnetic oscillations also can never cease completely. Thus the quantum nature of the electromagnetic field has as its consequence zero point oscillations of the field strength in the lowest energy state, in which there are no light quanta in space ... The zero point oscillations act on an electron in the same way as ordinary electrical oscillations do. They can change the eigenstate of the electron, but only in a transition to a state with the lowest energy, since empty space can only take away energy, and not give it up. In this way spontaneous radiation arises as a consequence of the existence of these unique field strengths corresponding to zero point oscillations. Thus spontaneous radiation is induced radiation of light quanta produced by zero point oscillations of empty space

This view was also later supported by [Theodore Welton](#) (1948),^[59] who argued that spontaneous emission "can be thought of as forced emission taking place under the action of the fluctuating field". This new theory, which Dirac coined [quantum electrodynamics](#) (QED), predicted a fluctuating zero-point or "vacuum" field existing even in the absence of sources.

Throughout the 1940s improvements in [microwave](#) technology made it possible to take more precise measurements of the shift of the levels of a [hydrogen atom](#), now known as the Lamb shift,^[60] and measurement of the [magnetic moment](#) of the electron.^[61] Discrepancies between these experiments and Dirac's theory led to the idea of incorporating [renormalisation](#) into QED to deal with zero-point infinities. Renormalization was originally developed by [Hans Kramers](#)^[62] and also [Victor Weisskopf](#) (1936),^[63] and first successfully applied to calculate a finite value for the Lamb shift by [Hans Bethe](#) (1947).^[64] As per spontaneous emission, these effects can in part be understood with interactions with the zero-point field.^{[65][11]} But in light of renormalisation being able to remove some zero-point infinities from calculations, not all physicists were comfortable attributing zero-point energy any physical meaning, viewing it instead as a mathematical artifact that might one day be eliminated. In [Wolfgang Pauli's](#) 1945 [Nobel lecture](#)^[66] he made clear his opposition to the idea of zero-point energy stating "It is clear that this zero-point energy has no physical reality".



Hendrik Casimir (1958)

In 1948 [Hendrik Casimir](#)^{[67][68]} showed that one consequence of the zero-point field is an attractive force between two uncharged, perfectly conducting parallel plates, the so-called Casimir effect. At the time, Casimir was studying the properties of [colloidal solutions](#). These are viscous materials, such as paint and mayonnaise, that contain micron-sized particles in a liquid matrix. The properties of such solutions are determined by [Van der Waals forces](#) – short-range, attractive forces that exist between neutral atoms and molecules. One of Casimir's colleagues, Theo Overbeek, realized that the theory that was used at the time to explain Van der Waals forces, which had been developed by [Fritz London](#) in 1930,^{[69][70]} did not properly explain the experimental measurements on colloids. Overbeek therefore asked Casimir to investigate the problem. Working with [Dirk Polder](#), Casimir discovered that the interaction between two neutral molecules could be correctly described only if the fact that light travels at a finite speed was taken into account.^[71] Soon afterwards after a conversation with [Bohr](#) about zero-point energy, Casimir noticed that this result could be interpreted in terms of vacuum fluctuations. He then asked himself what would happen if there were two mirrors – rather than two molecules – facing each other in a vacuum. It was this work that led to his prediction of an attractive force between reflecting plates. The work by Casimir and Polder opened up the way to a unified theory of van der Waals and Casimir forces and a smooth continuum between the two phenomena. This was done by Lifshitz (1956)^{[72][73][74]} in the case of plane parallel [dielectric plates](#). The generic name for both van der Waals and Casimir forces is dispersion forces, because both of them are caused by dispersions of the operator of the dipole moment.^[75] The role of relativistic forces becomes dominant at orders of a hundred nanometers.

In 1951 [Herbert Callen](#) and Theodore Welton^[76] proved the quantum [fluctuation-dissipation theorem](#) (FDT) which was originally formulated in classical form by [Nyquist](#) (1928)^[77] as an explanation for observed [Johnson noise](#) in electric circuits.^[78] The fluctuation-dissipation theorem showed that when something dissipates energy, in an effectively irreversible way, a connected heat bath must also fluctuate. The fluctuations and the dissipation go hand in hand; it is impossible to have one without the other. The implication of FDT being that the vacuum could be treated as a heat bath coupled to a dissipative force and as such energy could, in part, be extracted from the vacuum for potentially useful work.^[79] FDT has been shown to be true experimentally under certain quantum, non-classical, conditions.^{[80][81][82]}

In 1963 the [Jaynes–Cummings model](#)^[83] was developed describing the system of a [two-level atom](#) interacting with a quantized field mode (i.e. the vacuum) within an optical cavity. It gave nonintuitive predictions such as that an atom's spontaneous emission could be driven by field of effectively constant frequency ([Rabi frequency](#)). In the 1970s experiments were being performed to test aspects of quantum optics and showed that the rate of spontaneous emission of an atom could be controlled using reflecting surfaces.^{[84][85]} These results were at first regarded with suspicion in some quarters: it was argued that no modification of a spontaneous emission rate would be possible, after all, how can the emission of a photon be affected by an atom's environment when the atom can only "see" its environment by emitting a photon in the first place? These experiments gave rise to [cavity quantum electrodynamics](#) (CQED), the study of effects of mirrors and cavities on radiative corrections. Spontaneous emission can be

suppressed (or "inhibited")^{[86][87]} or amplified. Amplification was first predicted by Purcell in 1946^[88] (the [Purcell effect](#)) and has been experimentally verified.^[89] This phenomenon can be understood, partly, in terms of the action of the vacuum field on the atom.^[90]

Uncertainty principle

Zero-point energy is fundamentally related to the Heisenberg uncertainty principle.^[91] Roughly speaking, the uncertainty principle states that complementary variables (such as a particle's position and [momentum](#), or a field's value and derivative at a point in space) cannot simultaneously be specified precisely by any given quantum state. In particular, there cannot exist a state in which the system simply sits motionless at the bottom of its potential well, for then its position and momentum would both be completely determined to arbitrarily great precision. Therefore, the lowest-energy state (the ground state) of the system must have a distribution in position and momentum that satisfies the uncertainty principle, which implies its energy must be greater than the minimum of the potential well.

Near the bottom of a [potential well](#), the [Hamiltonian](#) of a general system (the quantum-mechanical [operator](#) giving its energy) can be approximated as a [quantum harmonic](#)

[oscillator](#), where V_0 is the minimum of the classical potential well.

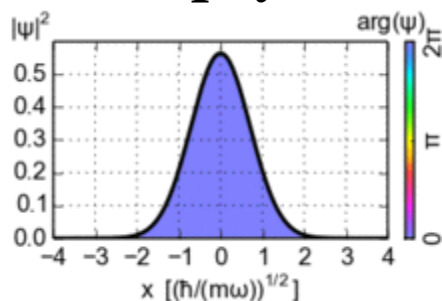
The uncertainty principle tells us that making the [expectation values](#) of the kinetic and [potential](#) terms above satisfy

The expectation value of the energy must therefore be at least

where $\omega = \sqrt{k/m}$ is the [angular frequency](#) at which the system oscillates.

A more thorough treatment, showing that the energy of the ground state actually saturates this bound and is exactly $E_0 = V_0 + \hbar\omega/2$, requires solving for the ground state of the system.

Atomic physics



The zero-point energy $E = \hbar\omega/2$ causes the ground-state of a harmonic oscillator to advance its phase (color). This has measurable effects when several eigenstates are superimposed.

The idea of a quantum harmonic oscillator and its associated energy can apply to either an atom or a subatomic particle. In ordinary atomic physics, the zero-point energy is the energy associated with the [ground state](#) of the system. The professional physics literature tends to measure frequency, as denoted by ν above, using [angular frequency](#), denoted with ω and defined by $\omega = 2\pi\nu$. This leads to a convention of writing the Planck constant h with a bar through its top ($\hbar$) to denote the quantity $h/2\pi$. In these terms, an example of zero-point energy is the above $E = \hbar\omega/2$ associated with the ground state of the quantum harmonic oscillator. In quantum mechanical terms, the zero-point energy is the [expectation value](#) of the Hamiltonian of the system in the ground state.

If more than one ground state exists, they are said to be [degenerate](#). Many systems have degenerate ground states. Degeneracy occurs whenever there exists a [unitary operator](#) which acts non-trivially on a ground state and [commutes](#) with the Hamiltonian of the system.

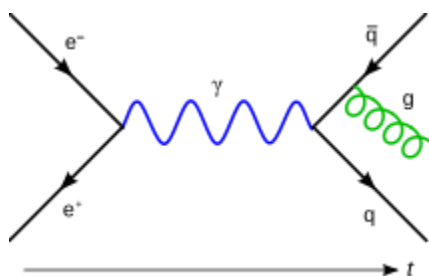
According to the [third law of thermodynamics](#), a system at absolute zero temperature exists in its ground state; thus, its [entropy](#) is determined by the degeneracy of the ground state. Many systems, such as a perfect [crystal lattice](#), have a unique ground state and therefore have zero entropy at absolute zero. It is also possible for the highest excited state to have absolute zero temperature for systems that exhibit [negative temperature](#).

The [wave function](#) of the ground state of a [particle in a one-dimensional well](#) is a half-period [sine wave](#) which goes to zero at the two edges of the well. The energy of the

particle is given by: where h is the [Planck constant](#), m is the mass of the particle, n is the energy state ($n = 1$ corresponds to the ground-state energy), and L is the width of the well.

Quantum field theory

Quantum field theory



Feynman diagram

In quantum field theory (QFT), the fabric of "empty" space is visualized as consisting of [fields](#), with the field at every point in space and time being a quantum harmonic oscillator, with neighboring oscillators interacting with each other. According to QFT the universe is made up of matter fields whose [quanta](#) are fermions (e.g. [electrons](#) and quarks), force fields whose quanta are bosons (i.e. photons and gluons) and a Higgs field whose quantum is the [Higgs boson](#). The matter and force fields have zero-point energy.^[2] A related term is *zero-point field* (ZPF), which is the lowest energy state of a particular field.^[92] The vacuum can be viewed not as empty space, but as the combination of all zero-point fields.

In QFT the zero-point energy of the vacuum state is called the vacuum energy and the average expectation value of the Hamiltonian is called the vacuum expectation value (also called condensate or simply VEV). The QED vacuum is a part of the vacuum state which specifically deals with quantum electrodynamics (e.g. electromagnetic interactions between photons, electrons and the vacuum) and the QCD vacuum deals with [quantum chromodynamics](#) (e.g. [color charge](#) interactions between quarks, gluons and the vacuum). Recent experiments advocate the idea that particles themselves can be thought of as excited states of the underlying [quantum vacuum](#), and that all properties of matter are merely vacuum fluctuations arising from interactions with the zero-point field.^[9]

Each point in space makes a contribution of $E = \hbar\omega/2$, resulting in a calculation of infinite zero-point energy in any finite volume; this is one reason [renormalization](#) is needed to make sense of quantum field theories. In [cosmology](#), the vacuum energy is one possible explanation for the cosmological constant^[18] and the source of dark energy.^{[19][20]}

Scientists are not in agreement about how much energy is contained in the vacuum. Quantum mechanics requires the energy to be large as [Paul Dirac](#) claimed it is, like a [sea of energy](#). Other scientists specializing in [General Relativity](#) require the energy to be small enough for [curvature of space](#) to agree with observed [astronomy](#). The Heisenberg uncertainty principle allows the energy to be as large as needed to promote quantum actions for a brief moment of time, even if the average energy is small enough to satisfy relativity and flat space. To cope with disagreements, the vacuum energy is described as a [virtual energy potential](#) of positive and negative energy.^[93]

In quantum [perturbation theory](#), it is sometimes said that the contribution of [one-loop](#) and multi-loop [Feynman diagrams](#) to [elementary particle propagators](#) are the contribution of [vacuum fluctuations](#), or the zero-point energy to the particle [masses](#).

Quantum electrodynamic vacuum

The oldest and best known quantized force field is the [electromagnetic field](#). [Maxwell's equations](#) have been superseded by quantum electrodynamics (QED). By considering the zero-point energy that arises from QED it is possible to gain a characteristic

understanding of zero-point energy that arises not just through electromagnetic interactions but in all [quantum field theories](#).

Redefining the zero of energy

In the quantum theory of the electromagnetic field, classical wave

amplitudes α and α^* are replaced by operators a and $a^\dagger$ that satisfy:

The classical quantity $|\alpha|^2$ appearing in the classical expression for the energy of a field mode is replaced in quantum theory by the photon number operator $a^\dagger a$. The fact that:

implies that quantum theory does not allow states of the radiation field for which the photon number and a field amplitude can be precisely defined, i.e., we cannot have simultaneous eigenstates for $a^\dagger a$ and a . The reconciliation of wave and particle attributes of the field is accomplished via the association of a probability amplitude with a classical mode pattern. The calculation of field modes is entirely classical problem, while the quantum properties of the field are carried by the mode

"amplitudes" $a^\dagger$ and a associated with these classical modes.

The zero-point energy of the field arises formally from the non-commutativity of a and $a^\dagger$. This is true for any harmonic oscillator: the zero-point energy $\hbar\omega/2$ appears

when we write the Hamiltonian:

It is often argued that the entire universe is completely bathed in the zero-point electromagnetic field, and as such it can add only some constant amount to expectation values. Physical measurements will therefore reveal only deviations from the vacuum state. Thus the zero-point energy can be dropped from the Hamiltonian by redefining the zero of energy, or by arguing that it is a constant and therefore has no effect on Heisenberg equations of motion. Thus we can choose to declare by fiat that the ground

state has zero energy and a field Hamiltonian, for example, can be replaced by:^[10] without affecting any physical predictions of the theory. The new Hamiltonian is said to be [normally ordered](#) (or Wick ordered) and is denoted by a double-dot symbol. The

normally ordered Hamiltonian is denoted $:H_F$, i.e.:

In other words, within the normal ordering symbol we can commute a and $a^\dagger$. Since zero-point energy is intimately connected to the non-commutativity of a and $a^\dagger$, the normal ordering procedure eliminates any contribution from the zero-point field. This is especially reasonable in the case of the field Hamiltonian, since the zero-point term merely adds a constant energy which can be eliminated by a simple redefinition for the zero of energy. Moreover, this constant energy in the Hamiltonian obviously commutes with a and $a^\dagger$ and so cannot have any effect on the quantum dynamics described by the Heisenberg equations of motion.

However, things are not quite that simple. The zero-point energy cannot be eliminated by dropping its energy from the Hamiltonian: When we do this and solve the Heisenberg equation for a field operator, we must include the vacuum field, which is the homogeneous part of the solution for the field operator. In fact we can show that the vacuum field is essential for the preservation of the commutators and the formal consistency of QED. When we calculate the field energy we obtain not only a contribution from particles and forces that may be present but also a contribution from the vacuum field itself i.e. the zero-point field energy. In other words, the zero-point energy reappears even though we may have deleted it from the Hamiltonian.^[94]

Electromagnetic field in free space

From Maxwell's equations, the electromagnetic energy of a "free" field i.e. one with no sources, is described by:

We introduce the "mode function" $\mathbf{A}_0(\mathbf{r})$ that satisfies the [Helmholtz equation](#):

where $k = \omega/c$ and assume it is normalized such that:

We wish to "quantize" the electromagnetic energy of free space for a multimode field. The field intensity of free space should be independent of position such that $|\mathbf{A}_0(\mathbf{r})|^2$ should be independent of $\mathbf{r}$ for each mode of the field. The mode function

satisfying these conditions is: where $\mathbf{k} \cdot \mathbf{e}_k = 0$ in order to have the transversality condition $\nabla \cdot \mathbf{A}(\mathbf{r}, t)$ satisfied for the Coulomb gauge^[dubious – discuss] in which we are working. To achieve the desired normalization we pretend space is divided into cubes of

volume $V = L^3$ and impose on the field the periodic boundary condition: or

equivalently where n can assume any integer value. This allows us to consider the field in any one of the imaginary cubes and to define the mode function: which

satisfies the Helmholtz equation, transversality, and the "box normalization":

where $\mathbf{e}_k$ is chosen to be a unit vector which specifies the polarization of the field mode.

The condition $\mathbf{k} \cdot \mathbf{e}_k = 0$ means that there are two independent choices of $\mathbf{e}_k$, which we call $\mathbf{e}_{k1}$ and $\mathbf{e}_{k2}$ where $\mathbf{e}_{k1} \cdot \mathbf{e}_{k2} = 0$ and e^2

$\mathbf{e}_{k1} = \mathbf{e}^2$

$\mathbf{e}_{k2} = 1$. Thus we define the mode functions: in terms of which the vector potential

becomes^[clarification needed]: or: where $\omega_k = kc$ and $a_{k\lambda}, a^\dagger$

$a_{k\lambda}$ are photon annihilation and creation operators for the mode with wave vector k and polarization λ . This gives the vector potential for a plane wave mode of the field. The condition for (k_x, k_y, k_z) shows that there are infinitely many such modes. The linearity of

Maxwell's equations allows us to write: for the total vector potential in free space.

Using the fact that: we find the field Hamiltonian is:

This is the Hamiltonian for an infinite number of uncoupled harmonic oscillators. Thus

different modes of the field are independent and satisfy the commutation relations:

Clearly the least eigenvalue for H_F is:

This state describes the zero-point energy of the vacuum. It appears that this sum is

divergent – in fact highly divergent, as putting in the density factor shows. The

summation becomes approximately the integral: for high values of v . It diverges proportional to v^4 for large v .

There are two separate questions to consider. First, is the divergence a real one such that the zero-point energy really is infinite? If we consider the volume V is contained by perfectly conducting walls, very high frequencies can only be contained by taking more and more perfect conduction. No actual method of containing the high frequencies is possible. Such modes will not be stationary in our box and thus not countable in the stationary energy content. So from this physical point of view the above sum should only extend to those frequencies which are countable; a cut-off energy is thus eminently reasonable. However, on the scale of a "universe" questions of general relativity must be included. Suppose even the boxes could be reproduced, fit together and closed nicely by curving spacetime. Then exact conditions for running waves may be possible. However the very high frequency quanta will still not be contained. As per John Wheeler's "geons"^[95] these will leak out of the system. So again a cut-off is permissible, almost necessary. The question here becomes one of consistency since the very high energy quanta will act as a mass source and start curving the geometry.

This leads to the second question. Divergent or not, finite or infinite, is the zero-point energy of any physical significance? The ignoring of the whole zero-point energy is often encouraged for all practical calculations. The reason for this is that energies are not typically defined by an arbitrary data point, but rather changes in data points, so adding or subtracting a constant (even if infinite) should be allowed. However this is not the whole story, in reality energy is not so arbitrarily defined: in general relativity the seat of the curvature of spacetime is the energy content and there the absolute amount of energy has real physical meaning. There is no such thing as an arbitrary additive constant with density of field energy. Energy density curves space, and an increase in energy density produces an increase of curvature. Furthermore, the zero-point energy density has other physical consequences e.g. the Casimir effect, contribution to the Lamb shift, or anomalous magnetic moment of the electron, it is clear it is not just a mathematical constant or artifact that can be cancelled out.^[96]

Necessity of the vacuum field in QED

The vacuum state of the "free" electromagnetic field (that with no sources) is defined as the ground state in which $n_{\mathbf{k}\lambda} = 0$ for all modes $(\mathbf{k}, \lambda)$. The vacuum state, like all stationary states of the field, is an eigenstate of the Hamiltonian but not the electric and magnetic field operators. In the vacuum state, therefore, the electric and magnetic fields do not have definite values. We can imagine them to be fluctuating about their mean value of zero.^[citation needed]

In a process in which a photon is annihilated (absorbed), we can think of the photon as making a transition into the vacuum state. Similarly, when a photon is created (emitted), it is occasionally useful to imagine that the photon has made a transition out of the vacuum state.^[54] An atom, for instance, can be considered to be "dressed" by emission and reabsorption of "virtual photons" from the vacuum. The vacuum state energy

described by $\sum_{\mathbf{k}\lambda} \hbar\omega_{\mathbf{k}}/2$ is infinite. We can make the replacement: the zero-point energy density is: or in other words the spectral energy density of the vacuum field:

The zero-point energy density in the frequency range from ω_1 to ω_2 is therefore:

This can be large even in relatively narrow "low frequency" regions of the spectrum. In the optical region from 400 to 700 nm, for instance, the above equation yields around 220 erg/cm³.

We showed in the above section that the zero-point energy can be eliminated from the Hamiltonian by the normal ordering prescription. However, this elimination does not mean that the vacuum field has been rendered unimportant or without physical consequences. To illustrate this point we consider a linear dipole oscillator in the

vacuum. The Hamiltonian for the oscillator plus the field with which it interacts is: This has the same form as the corresponding classical Hamiltonian and the Heisenberg equations of motion for the oscillator and the field are formally the same as their classical counterparts. For instance the Heisenberg equations for the coordinate $\mathbf{x}$ and

the canonical momentum $\mathbf{p} = m\dot{\mathbf{x}} + e\mathbf{A}/c$ of the oscillator are: or: since the rate of change of the vector potential in the frame of the moving charge is given by the

convective derivative

For nonrelativistic motion we may neglect the magnetic force and replace the

expression for $m\ddot{\mathbf{x}}$ by:

Above we have made the electric dipole approximation in which the spatial dependence of the field is neglected. The Heisenberg equation for $a_{\mathbf{k}\lambda}$ is found similarly from the

Hamiltonian to be: in the electric dipole approximation.

In deriving these equations for $\mathbf{x}$, $\mathbf{p}$, and $a_{k\lambda}$ we have used the fact that equal-time particle and field operators commute. This follows from the assumption that particle and field operators commute at some time (say, $t = 0$) when the matter-field interpretation is presumed to begin, together with the fact that a Heisenberg-picture operator $A(t)$ evolves in time as $A(t) = U^\dagger(t)A(0)U(t)$, where $U(t)$ is the time evolution

operator satisfying

Alternatively, we can argue that these operators must commute if we are to obtain the correct equations of motion from the Hamiltonian, just as the corresponding Poisson brackets in classical theory must vanish in order to generate the correct Hamilton

equations. The formal solution of the field equation is: and therefore the equation

for $\dot{a}_{k\lambda}$ may be written: where and

It can be shown that in the [radiation reaction](#) field, if the mass m is regarded as the

"observed" mass then we can take

The total field acting on the dipole has two parts, $\mathbf{E}_0(t)$ and $\mathbf{E}_{RR}(t)$. $\mathbf{E}_0(t)$ is the free or zero-point field acting on the dipole. It is the homogeneous solution of the Maxwell equation for the field acting on the dipole, i.e., the solution, at the position of the dipole,

of the wave equation satisfied by the field in the (source free) vacuum. For this reason $\mathbf{E}_0(t)$ is often referred to as the "vacuum field", although it is of course a Heisenberg-picture operator acting on whatever state of the field happens to be appropriate at $t = 0$. $\mathbf{E}_{RR}(t)$ is the source field, the field generated by the dipole and acting on the dipole.

Using the above equation for $\mathbf{E}_{RR}(t)$ we obtain an equation for the Heisenberg-picture

operator that is formally the same as the classical equation for a linear dipole

oscillator: where $\tau = 2e^2/3mc^3$. in this instance we have considered a dipole in the vacuum, without any "external" field acting on it. the role of the external field in the above equation is played by the vacuum electric field acting on the dipole.

Classically, a dipole in the vacuum is not acted upon by any "external" field: if there are no sources other than the dipole itself, then the only field acting on the dipole is its own radiation reaction field. In quantum theory however there is always an "external" field, namely the source-free or vacuum field $\mathbf{E}_0(t)$.

According to our earlier equation for $a_{k\lambda}(t)$ the free field is the only field in existence at $t = 0$ as the time at which the interaction between the dipole and the field is "switched

on". The state vector of the dipole-field system at $t = 0$ is therefore of the form where $|\text{vac}\rangle$ is the vacuum state of the field and $|\psi_D\rangle$ is the initial state of the dipole oscillator. The expectation value of the free field is therefore at all times equal to zero:

since $a_{\mathbf{k}\lambda}(0)|\text{vac}\rangle = 0$. however, the energy density associated with the free field is

infinite:

The important point of this is that the zero-point field energy H_F does not affect the Heisenberg equation for $a_{\mathbf{k}\lambda}$ since it is a c-number or constant (i.e. an ordinary number rather than an operator) and commutes with $a_{\mathbf{k}\lambda}$. We can therefore drop the zero-point field energy from the Hamiltonian, as is usually done. But the zero-point field re-emerges as the homogeneous solution for the field equation. A charged particle in the vacuum will therefore always see a zero-point field of infinite density. This is the origin of one of the infinities of quantum electrodynamics, and it cannot be eliminated by the trivial expedient dropping of the term $\sum_{\mathbf{k}\lambda} \hbar\omega_{\mathbf{k}}/2$ in the field Hamiltonian.

The free field is in fact necessary for the formal consistency of the theory. In particular, it is necessary for the preservation of the commutation relations, which is required by the

unitary of time evolution in quantum theory:

We can calculate $[z(t), p_z(t)]$ from the formal solution of the operator equation of motion

Using the fact that $\frac{d}{dt}[z(t), p_z(t)] = 0$ and that equal-time particle and field operators commute, we

obtain:

For the dipole oscillator under consideration it can be assumed that the radiative damping rate is small compared with the natural oscillation frequency, i.e., $\tau\omega_0 \ll 1$.

Then the integrand above is sharply peaked at $\omega = \omega_0$ and: the necessity of the vacuum field can also be appreciated by making the small damping approximation in

and

Without the free field $\mathbf{E}_0(t)$ in this equation the operator $\mathbf{x}(t)$ would be exponentially dampened, and commutators like $[z(t), p_z(t)]$ would approach zero for $t \gg 1/\tau\omega^2$

o. With the vacuum field included, however, the commutator is $i\hbar$ at all times, as required by unitarity, and as we have just shown. A similar result is easily worked out for the case of a free particle instead of a dipole oscillator.^[97]

What we have here is an example of a "fluctuation-dissipation relation". Generally speaking if a system is coupled to a bath that can take energy from the system in an effectively irreversible way, then the bath must also cause fluctuations. The fluctuations and the dissipation go hand in hand we cannot have one without the other. In the current example the coupling of a dipole oscillator to the electromagnetic field has a dissipative component, in the form of the zero-point (vacuum) field; given the existence of radiation reaction, the vacuum field must also exist in order to preserve the canonical commutation rule and all it entails.

The spectral density of the vacuum field is fixed by the form of the radiation reaction field, or vice versa: because the radiation reaction field varies with the third derivative of $\mathbf{x}$, the spectral energy density of the vacuum field must be proportional to the third power of ω in order for $[z(t), p_z(t)]$ to hold. In the case of a dissipative force proportional

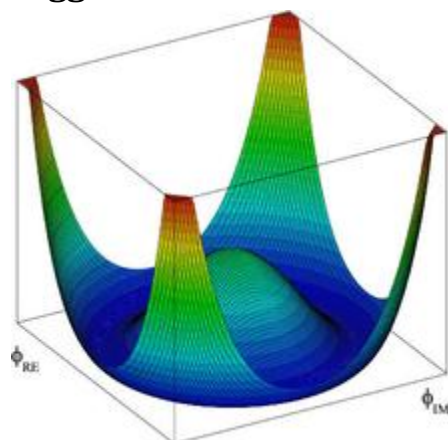
to $\dot{\mathbf{x}}$, by contrast, the fluctuation force must be proportional to $\dot{\mathbf{x}}$ in order to maintain the canonical commutation relation.^[97] This relation between the form of the dissipation and the spectral density of the fluctuation is the essence of the fluctuation-dissipation theorem.^[76]

The fact that the canonical commutation relation for a harmonic oscillator coupled to the vacuum field is preserved implies that the zero-point energy of the oscillator is preserved. It is easy to show that after a few damping times the zero-point motion of the oscillator is in fact sustained by the driving zero-point field.^[98]

Quantum chromodynamic vacuum

The QCD vacuum is the vacuum state of quantum chromodynamics (QCD). It is an example of a *non-perturbative* vacuum state, characterized by a non-vanishing *condensates* such as the *gluon condensate* and the *quark condensate* in the complete theory which includes quarks. The presence of these condensates characterizes the confined phase of *quark matter*. In technical terms, gluons are *vector gauge bosons* that mediate *strong interactions* of quarks in quantum chromodynamics (QCD). Gluons themselves carry the color charge of the strong interaction. This is unlike the photon, which mediates the *electromagnetic interaction* but lacks an electric charge. Gluons therefore participate in the strong interaction in addition to mediating it, making QCD significantly harder to analyze than QED (quantum electrodynamics) as it deals with *nonlinear equations* to characterize such interactions.

Higgs field



The potential for the Higgs field, plotted as function of ϕ^0 and ϕ^3 . It has a *Mexican-hat* or *champagne-bottle profile* at the ground.

The Standard Model hypothesises a field called the Higgs field (symbol: ϕ), which has the unusual property of a non-zero amplitude in its ground state (zero-point) energy after renormalization; i.e., a non-zero vacuum expectation value. It can have this effect

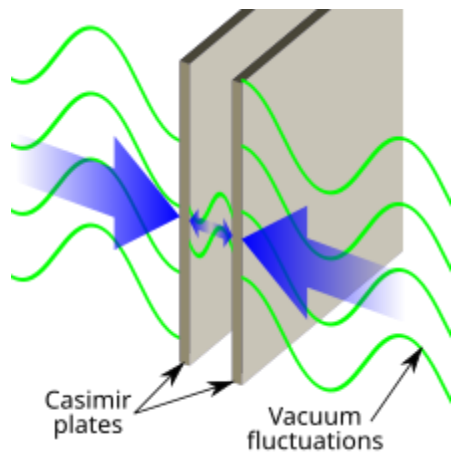
because of its unusual "Mexican hat" shaped potential whose lowest "point" is not at its "centre". Below a certain extremely high energy level the existence of this non-zero vacuum expectation [spontaneously breaks electroweak gauge symmetry](#) which in turn gives rise to the Higgs mechanism and triggers the acquisition of mass by those particles interacting with the field. The Higgs mechanism occurs whenever a charged field has a vacuum expectation value. This effect occurs because scalar field components of the Higgs field are "absorbed" by the massive bosons as degrees of freedom, and couple to the fermions via Yukawa coupling, thereby producing the expected mass terms. The expectation value of ϕ^0 in the ground state (the vacuum expectation value or VEV) is then $\langle \phi^0 \rangle = v/\sqrt{2}$, where $v = |\mu|/\sqrt{\lambda}$. The measured value of this parameter is approximately 246 GeV/c².^[99] It has units of mass, and is the only free parameter of the Standard Model that is not a dimensionless number.

The Higgs mechanism is a type of [superconductivity](#) which occurs in the vacuum. It occurs when all of space is filled with a sea of particles which are charged and thus the field has a nonzero vacuum expectation value. Interaction with the vacuum energy filling the space prevents certain forces from propagating over long distances (as it does in a superconducting medium; e.g., in the [Ginzburg–Landau theory](#)).

Experimental observations

Zero-point energy has many observed physical consequences.^[11] It is important to note that zero-point energy is not merely an artifact of mathematical formalism that can, for instance, be dropped from a Hamiltonian by redefining the zero of energy, or by arguing that it is a constant and therefore has no effect on Heisenberg equations of motion without latter consequence.^[100] Indeed, such treatment could create a problem at a deeper, as of yet undiscovered, theory.^[101] For instance, in general relativity the zero of energy (i.e. the energy density of the vacuum) contributes to a cosmological constant of the type introduced by Einstein in order to obtain static solutions to his field equations.^[102] The zero-point energy density of the vacuum, due to all quantum fields, is extremely large, even when we cut off the largest allowable frequencies based on plausible physical arguments. It implies a cosmological constant larger than the limits imposed by observation by about 120 orders of magnitude. This "cosmological constant problem" remains one of the greatest unsolved mysteries of physics.^[103]

Casimir effect



Casimir forces on parallel plates

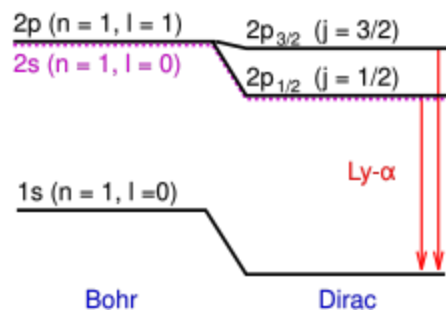
A phenomenon that is commonly presented as evidence for the existence of zero-point energy in vacuum is the Casimir effect, proposed in 1948 by Dutch physicist Hendrik Casimir, who considered the quantized electromagnetic field between a pair of grounded, neutral metal plates. The vacuum energy contains contributions from all wavelengths, except those excluded by the spacing between plates. As the plates draw together, more wavelengths are excluded and the vacuum energy decreases. The decrease in energy means there must be a force doing work on the plates as they move.

Early experimental tests from the 1950s onwards gave positive results showing the force was real, but other external factors could not be ruled out as the primary cause, with the range of experimental error sometimes being nearly 100%.^{[104][105][106][107][108]} That changed in 1997 with Lamoreaux^[109] conclusively showing that the Casimir force was real. Results have been repeatedly replicated since then.^{[110][111][112][113]}

In 2009, Munday et al.^[114] published experimental proof that (as predicted in 1961^[115]) the Casimir force could also be repulsive as well as being attractive. Repulsive Casimir forces could allow quantum levitation of objects in a fluid and lead to a new class of switchable nanoscale devices with ultra-low static friction.^[116]

An interesting hypothetical side effect of the Casimir effect is the Scharnhorst effect, a hypothetical phenomenon in which light signals travel slightly faster than c between two closely spaced conducting plates.^[117]

Lamb shift



Fine structure of energy levels in hydrogen – relativistic corrections to the **Bohr model**

The quantum fluctuations of the electromagnetic field have important physical consequences. In addition to the Casimir effect, they also lead to a splitting between the two **energy levels** $^2S_{1/2}$ and $^2P_{1/2}$ (in **term symbol** notation) of the **hydrogen atom** which was not predicted by the **Dirac equation**, according to which these states should have the same energy. Charged particles can interact with the fluctuations of the quantized vacuum field, leading to slight shifts in energy;^[118] this effect is called the Lamb shift.^[119] The shift of about 4.38×10^{-6} eV is roughly 10^{-7} of the difference between the energies of the 1s and 2s levels, and amounts to 1,058 MHz in frequency units. A small part of this shift (27 MHz $\approx$ 3%) arises not from fluctuations of the electromagnetic field, but from fluctuations of the electron–positron field. The creation of (virtual) electron–positron pairs has the effect of screening the Coulomb field and acts as a vacuum dielectric constant. This effect is much more important in muonic atoms.^[120]

Fine-structure constant

Taking $\hbar$ (the **Planck constant** divided by 2π), c (the **speed of light**), and $e^2 = q^2 / 4\pi\epsilon_0$ (the electromagnetic **coupling constant** i.e. a measure of the strength of the **electromagnetic force** (where q_e is the absolute value of the **electronic**

charge and ϵ_0 is the **vacuum permittivity**)) we can form a dimensionless quantity

called the **fine-structure constant**:

The fine-structure constant is the coupling constant of quantum electrodynamics (QED) determining the strength of the interaction between electrons and photons. It turns out that the fine-structure constant is not really a constant at all owing to the zero-point energy fluctuations of the electron-positron field.^[121] The quantum fluctuations caused by zero-point energy have the effect of screening electric charges: owing to (virtual) electron-positron pair production, the charge of the particle measured far from the particle is far smaller than the charge measured when close to it.

The Heisenberg inequality where $\hbar = h/2\pi$, and Δ_x , Δ_p are the standard deviations of

position and momentum states that:

It means that a short distance implies large momentum and therefore high energy i.e. particles of high energy must be used to explore short distances. QED concludes that the fine-structure constant is an increasing function of energy. It has been shown that at

energies of the order of the **Z⁰ boson** rest energy, $m_Z c^2 \approx 90$ GeV, that: rather than the low-energy $\alpha \approx 1/137$.^{[122][123]} The renormalization procedure of eliminating zero-point energy infinities allows the choice of an arbitrary energy (or distance) scale for defining α . All in all, α depends on the energy scale characteristic of the process under study, and also on details of the renormalization procedure. The energy dependence of α has been observed for several years now in precision experiment in high-energy physics.

Vacuum birefringence

Lorentz-violating electrodynamics and Euler–Heisenberg Lagrangian

Light coming from the surface of a strongly magnetic [neutron star](#) (left) becomes linearly polarised as it travels through the vacuum.

In the presence of strong electrostatic fields it is predicted that virtual particles become separated from the vacuum state and form real matter.^[citation needed] The fact that electromagnetic radiation can be transformed into matter and vice versa leads to fundamentally new features in quantum electrodynamics. One of the most important consequences is that, even in the vacuum, the Maxwell equations have to be exchanged by more complicated formulas. In general, it will be not possible to separate processes in the vacuum from the processes involving matter since electromagnetic fields can create matter if the field fluctuations are strong enough. This leads to highly complex nonlinear interaction – gravity will have an effect on the light at the same time the light has an effect on gravity. These effects were first predicted by Werner Heisenberg and [Hans Heinrich Euler](#) in 1936^[124] and independently the same year by Victor Weisskopf who stated: "The physical properties of the vacuum originate in the "zero-point energy" of matter, which also depends on absent particles through the external field strengths and therefore contributes an additional term to the purely Maxwellian field energy".^{[125][126]} Thus strong magnetic fields vary the energy contained in the vacuum. The scale above which the electromagnetic field is expected to become nonlinear is known as the [Schwinger limit](#). At this point the vacuum has all the properties of a [birefringent medium](#), thus in principle a rotation of the polarization frame (the [Faraday effect](#)) can be observed in empty space.^{[127][128]}



Wide field view of the neutron star [RX J1856.5-3754](#)

Both Einstein's theory of special and general relativity state that light should pass freely through a vacuum without being altered, a principle known as [Lorentz invariance](#). Yet, in theory, large nonlinear self-interaction of light due to quantum fluctuations should lead to this principle being measurably violated if the interactions are strong enough. Nearly all theories of [quantum gravity](#) predict that Lorentz invariance is not an exact symmetry of nature. It is predicted the speed at which light travels through the vacuum depends on its direction, polarization and the local strength of the magnetic field.^[129] There have been a number of inconclusive results which claim to show evidence of a [Lorentz](#)

violation by finding a rotation of the polarization plane of light coming from distant galaxies.^[130] The first concrete evidence for vacuum birefringence was published in 2017 when a team of astronomers looked at the light coming from the star RX J1856.5-3754,^[131] the closest discovered neutron star to Earth.^[132]

Roberto Mignani at the National Institute for Astrophysics in Milan who led the team of astronomers has commented that "When Einstein came up with the theory of general relativity 100 years ago, he had no idea that it would be used for navigational systems. The consequences of this discovery probably will also have to be realised on a longer timescale."^[133] The team found that visible light from the star had undergone linear polarisation^[clarification needed] of around 16%. If the birefringence had been caused by light passing through interstellar gas or plasma, the effect should have been no more than 1%. Definitive proof would require repeating the observation at other wavelengths and on other neutron stars. At X-ray wavelengths the polarization from the quantum fluctuations should be near 100%.^[134] Although no telescope currently exists that can make such measurements, there are several proposed X-ray telescopes that may soon be able to verify the result conclusively such as China's Hard X-ray Modulation Telescope (HXMT) and NASA's Imaging X-ray Polarimetry Explorer (IXPE).

Speculated involvement in other phenomena

Dark energy

Unsolved problem in physics:

Why does the large zero-point energy of the vacuum not cause a large cosmological constant? What cancels it out?^{[18][103][135]}

(more unsolved problems in physics)

In the late 1990s it was discovered that very distant supernovae were dimmer than expected suggesting that the universe's expansion was accelerating rather than slowing down.^{[136][137]} This revived discussion that Einstein's cosmological constant, long disregarded by physicists as being equal to zero, was in fact some small positive value. This would indicate empty space exerted some form of negative pressure or energy.

There is no natural candidate for what might cause what has been called dark energy but the current best guess is that it is the zero-point energy of the vacuum, but this guess is known to be off by 120 orders of magnitude.^[138]

The European Space Agency's Euclid telescope, launched on 1 July 2023, will map galaxies up to 10 billion light years away.^[139] By seeing how dark energy influences their arrangement and shape, the mission will allow scientists to see if the strength of dark energy has changed. If dark energy is found to vary throughout time it would indicate it is due to quintessence, where observed acceleration is due to the energy of a scalar

field, rather than the cosmological constant. No evidence of quintessence is yet available, but it has not been ruled out either. It generally predicts a slightly slower acceleration of the expansion of the universe than the cosmological constant. Some scientists think that the best evidence for quintessence would come from violations of Einstein's [equivalence principle](#) and [variation of the fundamental constants](#) in space or time.^[140] Scalar fields are predicted by the *Standard Model of particle physics* and [string theory](#), but an analogous problem to the cosmological constant problem (or the problem of constructing models of [cosmological inflation](#)) occurs: [renormalization](#) theory predicts that scalar fields should acquire large masses again due to zero-point energy.

Cosmic inflation

Unsolved problem in physics:

Why does the observable universe have more matter than antimatter?

([more unsolved problems in physics](#))

[Cosmic inflation](#) is phase of accelerated [cosmic expansion](#) just after the Big Bang. It explains the origin of the [large-scale structure of the cosmos](#). It is believed [quantum vacuum fluctuations](#) caused by zero-point energy arising in the microscopic inflationary period, later became magnified to a cosmic size, becoming the gravitational seeds for galaxies and structure in the Universe (see [galaxy formation and evolution](#) and [structure formation](#)).^[141] Many physicists also believe that inflation explains why the Universe appears to be the same in all directions ([isotropic](#)), why the [cosmic microwave background](#) radiation is distributed evenly, why the Universe is flat, and why no [magnetic monopoles](#) have been observed.

The mechanism for inflation is unclear, it is similar in effect to dark energy but is a far more energetic and short lived process. As with dark energy the best explanation is some form of vacuum energy arising from quantum fluctuations. It may be that inflation caused [baryogenesis](#), the hypothetical physical processes that produced an [asymmetry](#) (imbalance) between [baryons](#) and antibaryons produced in the [very early universe](#), but this is far from certain.

Cosmology

[Paul S. Wesson](#) examined the cosmological implications of assuming that zero-point energy is real.^[142] Among numerous difficulties, [general relativity](#) requires that such energy not gravitate, so it cannot be similar to electromagnetic radiation.

Alternative theories

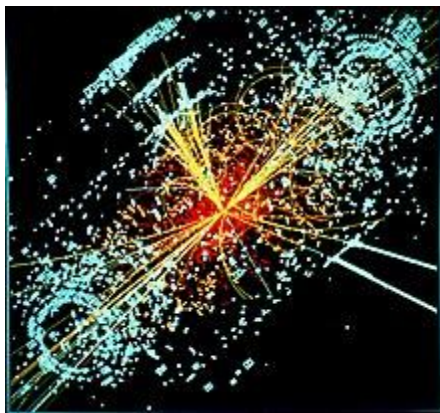
There has been a long debate^[143] over the question of whether zero-point fluctuations of quantized vacuum fields are "real" i.e. do they have physical effects that cannot be interpreted by an equally valid alternative theory? [Schwinger](#), in particular, attempted to formulate QED without reference to zero-point fluctuations via his "source theory".^[144] From such an approach it is possible to derive the Casimir Effect without reference to a fluctuating field. Such a derivation was first given by Schwinger (1975)^[145] for a scalar field, and then generalized to the electromagnetic case by

Schwinger, DeRaad, and Milton (1978).^[146] in which they state "the vacuum is regarded as truly a state with all physical properties equal to zero". Jaffe (2005)^[147] has highlighted a similar approach in deriving the Casimir effect stating "the concept of zero-point fluctuations is a heuristic and calculational aid in the description of the Casimir effect, but not a necessity in QED."

Milonni has shown the necessity of the vacuum field for the formal consistency of QED.^[148] Modern physics does not know any better way to construct gauge-invariant, renormalizable theories than with zero-point energy and they would seem to be a necessity for any attempt at a unified theory.^[149] Nevertheless, as pointed out by Jaffe, "no known phenomenon, including the Casimir effect, demonstrates that zero point energies are "real""^[147]

Chaotic and emergent phenomena

Beyond the Standard Model



Simulated [Large Hadron Collider CMS](#) particle detector data depicting a [Higgs boson](#) produced by colliding protons decaying into hadron jets and electrons

See also: [Chaos theory](#), [Emergence](#), and [Self-organization](#)

The mathematical models used in [classical electromagnetism](#), quantum electrodynamics (QED) and the [Standard Model](#) all view the [electromagnetic vacuum](#) as a linear system with no overall observable consequence. For example, in the case of the Casimir effect, Lamb shift, and so on these phenomena can be explained by alternative mechanisms other than action of the vacuum by arbitrary changes to the normal ordering of field operators. See the [alternative theories](#) section. This is a consequence of viewing electromagnetism as a U(1) gauge theory, which topologically does not allow the complex interaction of a field with and on itself.^[150] In higher symmetry groups and in reality, the vacuum is not a calm, randomly fluctuating, largely immaterial and passive substance, but at times can be viewed as a turbulent virtual [plasma](#) that can have complex vortices (i.e. [solitons](#) vis-à-vis particles), [entangled states](#) and a rich nonlinear structure.^[151] There are many observed nonlinear physical electromagnetic phenomena such as [Aharonov–Bohm](#) (AB)^{[152][153]} and [Altshuler–Aronov–Spivak](#) (AAS) effects,^[154] [Berry](#),^[155] [Aharonov–Anandan](#),^[156] [Pancharatnam](#)^[157] and [Chiao–Wu](#)^[158] phase rotation effects, [Josephson effect](#),^{[159][160]} [Quantum Hall effect](#),^[161] the [De Haas–Van Alphen effect](#),^[162] the [Sagnac effect](#) and many other physically observable phenomena which would indicate that the electromagnetic potential field has real physical meaning rather than being a mathematical artifact^[163] and therefore an all encompassing theory would not confine electromagnetism as a local force as is currently done, but as a SU(2) gauge theory or higher geometry. Higher symmetries allow for nonlinear, aperiodic behaviour which manifest as a variety of complex non-equilibrium phenomena that do not arise in the linearised U(1) theory, such as multiple stable states, symmetry breaking, chaos and [emergence](#).^[164]

What are called Maxwell's equations today, are in fact a simplified version of the original equations reformulated by [Heaviside](#), [FitzGerald](#), [Lodge](#) and [Hertz](#). The original equations used [Hamilton's](#) more expressive [quaternion](#) notation,^[165] a kind of [Clifford algebra](#), which fully subsumes the standard Maxwell vectorial equations largely used today.^[166] In the late 1880s there was a debate over the relative merits of vector analysis and quaternions. According to Heaviside the electromagnetic potential field was purely metaphysical, an arbitrary mathematical fiction, that needed to be "murdered".^[167] It was concluded that there was no need for the greater physical insights provided by the quaternions if the theory was purely local in nature. Local vector analysis has become the dominant way of using Maxwell's equations ever since. However, this strictly vectorial approach has led to a restrictive topological understanding in some areas of electromagnetism, for example, a full understanding of the energy transfer dynamics in [Tesla's](#) oscillator-shuttle-circuit can only be achieved in quaternionic algebra or higher SU(2) symmetries.^[168] It has often been argued that quaternions are not compatible with special relativity,^[169] but multiple papers have shown ways of incorporating relativity.^{[170][171][172][173]}

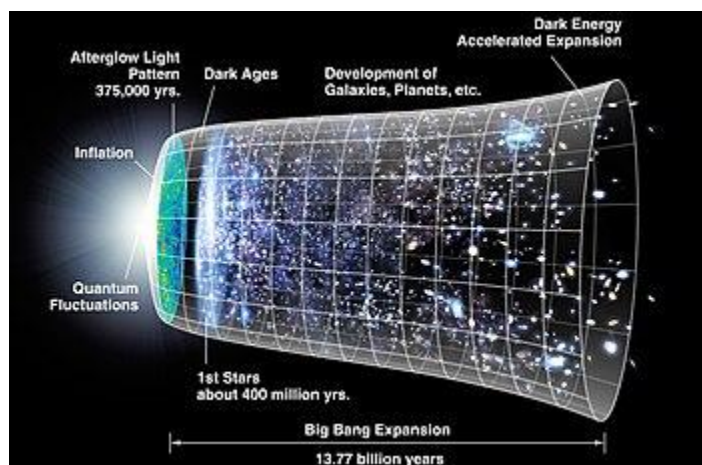
A good example of nonlinear electromagnetics is in high energy dense plasmas, where [vortical phenomena](#) occur which seemingly violate the [second law of thermodynamics](#) by increasing the energy gradient within the electromagnetic field and violate [Maxwell's laws](#) by creating ion currents which capture and concentrate their own

and surrounding magnetic fields. In particular [Lorentz force law](#), which elaborates Maxwell's equations is violated by these force free vortices.^{[174][175][176]} These apparent violations are due to the fact that the traditional conservation laws in classical and quantum electrodynamics (QED) only display linear U(1) symmetry (in particular, by the extended [Noether theorem](#),^[177] [conservation laws](#) such as the [laws of thermodynamics](#) need not always apply to [dissipative systems](#),^{[178][179]} which are expressed in gauges of higher symmetry). The second law of thermodynamics states that in a closed linear system entropy flow can only be positive (or exactly zero at the end of a cycle). However, negative entropy (i.e. increased order, structure or self-organisation) can spontaneously appear in an open nonlinear thermodynamic system that is far from equilibrium, so long as this emergent order accelerates the overall flow of entropy in the total system. The 1977 [Nobel Prize in Chemistry](#) was awarded to thermodynamicist [Ilya Prigogine](#)^[180] for his theory of dissipative systems that described this notion. Prigogine described the principle as "order through fluctuations"^[181] or "order out of chaos".^[182] It has been argued by some that all emergent order in the universe from galaxies, solar systems, planets, weather, complex chemistry, evolutionary biology to even consciousness, technology and civilizations are themselves examples of thermodynamic dissipative systems; nature having naturally selected these structures to accelerate entropy flow within the universe to an ever-increasing degree.^[183] For example, it has been estimated that human body is 10,000 times more effective at dissipating energy per unit of mass than the sun.^[184]

One may query what this has to do with zero-point energy. Given the complex and adaptive behaviour that arises from nonlinear systems considerable attention in recent years has gone into studying a new class of [phase transitions](#) which occur at absolute zero temperature. These are quantum phase transitions which are driven by EM field fluctuations as a consequence of zero-point energy.^[185] A good example of a spontaneous phase transition that are attributed to zero-point fluctuations can be found in [superconductors](#). Superconductivity is one of the best known empirically quantified macroscopic electromagnetic phenomena whose basis is recognised to be quantum mechanical in origin. The behaviour of the electric and magnetic fields under superconductivity is governed by the [London equations](#). However, it has been questioned in a series of journal articles whether the quantum mechanically canonised London equations can be given a purely classical derivation.^[186] Bostick,^{[187][188]} for instance, has claimed to show that the London equations do indeed have a classical origin that applies to superconductors and to some collisionless plasmas as well. In particular it has been asserted that the [Beltrami vortices](#) in the plasma focus display the same paired [flux-tube](#) morphology as [Type II superconductors](#).^{[189][190]} Others have also pointed out this connection, Fröhlich^[191] has shown that the hydrodynamic equations of compressible fluids, together with the London equations, lead to a macroscopic

parameter ($\beta = \text{electric charge density} / \text{mass density}$), without involving either [quantum phase factors](#) or the Planck constant. In essence, it has been asserted that Beltrami plasma vortex structures are able to at least simulate the morphology of [Type I](#) and [Type II superconductors](#). This occurs because the "organised" dissipative energy of the vortex configuration comprising the ions and electrons far exceeds the "disorganised" dissipative random thermal energy. The transition from disorganised

fluctuations to organised helical structures is a phase transition involving a change in the condensate's energy (i.e. the ground state or zero-point energy) but *without any associated rise in temperature*.^[192] This is an example of zero-point energy having multiple stable states (see [Quantum phase transition](#), [Quantum critical point](#), [Topological degeneracy](#), [Topological order](#)^[193]) and where the overall system structure is independent of a reductionist or deterministic view, that "classical" macroscopic order can also causally affect quantum phenomena. Furthermore, the pair production of Beltrami vortices has been compared to the morphology of pair production of virtual particles in the vacuum.



Artist's conception of the [expansion of the universe](#). On the left, the dramatic expansion occurs in the [inflationary epoch](#).

The idea that the vacuum energy can have multiple stable energy states is a leading hypothesis for the cause of [cosmic inflation](#). In fact, it has been argued that these early vacuum fluctuations led to the expansion of the universe and in turn have guaranteed the non-equilibrium conditions necessary to drive order from chaos, as without such expansion the universe would have reached thermal equilibrium and no complexity could have existed. With the continued accelerated expansion of the universe, the cosmos generates an energy gradient that increases the "free energy" (i.e. the available, usable or potential energy for useful work) which the universe is able to use to create ever more complex forms of order.^{[194][195]} The only reason Earth's environment does not decay into an equilibrium state is that it receives a daily dose of sunshine and that, in turn, is due to the sun "polluting" interstellar space with entropy. The sun's fusion power is only possible due to the gravitational disequilibrium of matter that arose from cosmic expansion. In this essence, the vacuum energy can be viewed as the key cause of the structure throughout the universe. That humanity might alter the morphology of the vacuum energy to create an energy gradient for useful work is the subject of much controversy.

Purported applications

Physicists overwhelmingly reject any possibility that the zero-point energy field can be exploited to obtain useful energy ([work](#)) or uncompensated momentum; such efforts are seen as tantamount to [perpetual motion machines](#).^[citation needed]

Nevertheless, the allure of free energy has motivated such research, usually falling in the category of [fringe science](#). As long ago as 1889 (before quantum theory or discovery of the zero point energy) [Nikola Tesla](#) proposed that useful energy could be obtained from free space, or what was assumed at that time to be an all-pervasive [aether](#).^[196] Others have since claimed to exploit zero-point or vacuum energy with a large amount of [pseudoscientific](#) literature causing ridicule around the subject.^{[197][198]} Despite rejection by the scientific community, harnessing zero-point energy remains an interest of research, particularly in the US where it has attracted the attention of major aerospace/defence contractors and the [U.S. Department of Defense](#) as well as in China, Germany, Russia and Brazil.^{[197][199]}

Casimir batteries and engines

A common assumption is that the [Casimir force](#) is of little practical use; the argument is made that the only way to actually gain energy from the two plates is to allow them to come together (getting them apart again would then require more energy), and therefore it is a one-use-only tiny force in nature.^[197] In 1984 [Robert Forward](#) published work showing how a "vacuum-fluctuation battery" could be constructed; the battery can be recharged by making the electrical forces slightly stronger than the Casimir force to reexpand the plates.^[200]

In 1999, Pinto, a former scientist at [NASA's Jet Propulsion Laboratory at Caltech](#) in Pasadena, published in [Physical Review](#) his [thought experiment](#) (Gedankenexperiment) for a "Casimir engine". The paper showed that continuous positive net exchange of energy from the Casimir effect was possible, even stating in the abstract "In the event of no other alternative explanations, one should conclude that major technological advances in the area of endless, by-product free-energy production could be achieved."^[201]

Garret Model at [University of Colorado](#) has highlighted that he believes such devices hinge on the assumption that the Casimir force is a [nonconservative force](#), he argues that there is sufficient evidence (e.g. analysis by Scandurra (2001)^[202]) to say that the Casimir effect is a conservative force and therefore even though such an engine can exploit the Casimir force for useful work it cannot produce more output energy than has been input into the system.^[203]

In 2008, [DARPA](#) solicited research proposals in the area of Casimir Effect Enhancement (CEE). The goal of the program is to develop new methods to control and manipulate attractive and repulsive forces at surfaces based on engineering of the Casimir force.^[204]

A 2008 patent by Haisch and Model^[205] details a device that is able to extract power from zero-point fluctuations using a gas that circulates through a Casimir cavity. A published test of this concept by Model^[206] was performed in 2012 and seemed to give excess energy that could not be attributed to another source. However it has not been conclusively shown to be from zero-point energy and the theory requires further investigation.^[207]

Single heat baths

In 1951 Callen and Welton^[76] proved the quantum [fluctuation-dissipation theorem](#) (FDT) which was originally formulated in classical form by Nyquist (1928)^[77] as an explanation for observed [Johnson noise](#)^[78] in electric circuits. Fluctuation-dissipation theorem showed that when something dissipates energy, in an effectively irreversible way, a connected heat bath must also fluctuate. The fluctuations and the dissipation go hand in hand; it is impossible to have one without the other. The implication of FDT being that the vacuum could be treated as a heat bath coupled to a dissipative force and as such energy could, in part, be extracted from the vacuum for potentially useful work.^[79] Such a theory has met with resistance: Macdonald (1962)^[208] and Harris (1971)^[209] claimed that extracting power from the zero-point energy to be impossible, so FDT could not be true. Grau and Kleen (1982)^[210] and Kleen (1986),^[211] argued that the Johnson noise of a resistor connected to an antenna must satisfy Planck's thermal radiation formula, thus the noise must be zero at zero temperature and FDT must be invalid. Kiss (1988)^[212] pointed out that the existence of the zero-point term may indicate that there is a renormalization problem—i.e., a mathematical artifact—producing an unphysical term that is not actually present in measurements (in analogy with renormalization problems of ground states in quantum electrodynamics). Later, Abbott et al. (1996) arrived at a different but unclear conclusion that "zero-point energy is infinite thus it should be renormalized but not the 'zero-point fluctuations'".^[213] Despite such criticism, FDT has been shown to be true experimentally under certain quantum, non-classical conditions. Zero-point fluctuations can, and do, contribute towards systems which dissipate energy.^[80] A paper by Armen Allahverdyan and Theo Nieuwenhuizen in 2000 showed the feasibility of extracting zero-point energy for useful work from a single bath, without contradicting the [laws of thermodynamics](#), by exploiting certain quantum mechanical properties.^[81]

There have been a growing number of papers showing that in some instances the classical laws of thermodynamics, such as limits on the Carnot efficiency, can be violated by exploiting negative entropy of quantum fluctuations.^{[82][214][215][216][217][218][219][220][221][222]}

Despite efforts to reconcile quantum mechanics and thermodynamics over the years, their compatibility is still an open fundamental problem. The full extent that quantum properties can alter classical thermodynamic bounds is unknown^[223]

Space travel and gravitational shielding

The use of zero-point energy for space travel is speculative and does not form part of the mainstream scientific consensus. A complete [quantum theory of gravitation](#) (that would deal with the role of quantum phenomena like zero-point energy) does not yet exist. Speculative papers explaining a relationship between zero-point energy and gravitational shielding effects have been proposed,^{[16][224][225][226]} but the interaction (if any) is not yet fully understood. According to the [general theory of relativity](#), rotating matter can generate a new force of nature, known as the gravitomagnetic interaction, whose intensity is proportional to the rate of spin.^[227] In certain conditions the gravitomagnetic field can be repulsive. In neutron stars for example, it can produce a gravitational

analogue of the [Meissner effect](#), but the force produced in such an example is theorized to be exceedingly weak.^[228]

In 1963 [Robert Forward](#), a physicist and aerospace engineer at [Hughes Research Laboratories](#), published a paper showing how within the framework of general relativity "anti-gravitational" effects might be achieved.^[229] Since all atoms have [spin](#), gravitational permeability may be able to differ from material to material. A strong [toroidal](#) gravitational field that acts against the force of gravity could be generated by materials that have [nonlinear properties](#) that enhance time-varying gravitational fields. Such an effect would be analogous to the nonlinear electromagnetic permeability of iron, making it an effective core (i.e. the doughnut of iron) in a transformer, whose properties are dependent on magnetic permeability.^{[230][231][232]} In 1966 [Dewitt](#)^[233] was first to identify the significance of gravitational effects in superconductors. Dewitt demonstrated that a magnetic-type gravitational field must result in the presence of [fluxoid quantization](#). In 1983, Dewitt's work was substantially expanded by Ross.^[234]

From 1971 to 1974 Henry William Wallace, a scientist at [GE Aerospace](#) was issued with three patents.^{[235][236][237]} Wallace used [Dewitt's](#) theory to develop an experimental apparatus for generating and detecting a secondary gravitational field, which he named the kinemassic field (now better known as the gravitomagnetic field). In his three patents, Wallace describes three different methods used for detection of the gravitomagnetic field – change in the motion of a body on a pivot, detection of a transverse voltage in a semiconductor crystal, and a change in the specific heat of a crystal material having spin-aligned nuclei. There are no publicly available independent tests verifying Wallace's devices. Such an effect if any would be small.^{[238][239][240][241][242][243]} Referring to Wallace's patents, a [New Scientist](#) article in 1980 stated "Although the Wallace patents were initially ignored as cranky, observers believe that his invention is now under serious but secret investigation by the military authorities in the USA. The military may now regret that the patents have already been granted and so are available for anyone to read."^[244] A further reference to Wallace's patents occur in an electric propulsion study prepared for the [Astronautics Laboratory](#) at [Edwards Air Force Base](#) which states: "The patents are written in a very believable style which include part numbers, sources for some components, and diagrams of data. Attempts were made to contact Wallace using patent addresses and other sources but he was not located nor is there a trace of what became of his work. The concept can be somewhat justified on general relativistic grounds since rotating frames of time varying fields are expected to emit gravitational waves."^[245]

In 1986 the [U.S. Air Force's](#) then Rocket Propulsion Laboratory (RPL) at [Edwards Air Force Base](#) solicited "Non Conventional Propulsion Concepts" under a small business research and innovation program. One of the six areas of interest was "Esoteric energy sources for propulsion, including the quantum dynamic energy of vacuum space..." In the same year [BAE Systems](#) launched "Project Greenglow" to provide a "focus for research into novel propulsion systems and the means to power them".^{[199][246]}

In 1988 [Kip Thorne](#) et al.^[247] published work showing how traversable [wormholes](#) can exist in spacetime only if they are threaded by quantum fields generated by some form of [exotic matter](#) that has [negative energy](#). In 1993 Scharnhorst and Barton^[117] showed that [the speed of a photon will be increased](#) if it travels between two Casimir plates, an example of negative energy. In the most general sense, the exotic matter needed to create wormholes would share the repulsive properties of the [inflationary energy](#), dark energy or zero-point radiation of the vacuum.^[248] Building on the work of Thorne, in 1994 [Miguel Alcubierre](#)^[249] proposed a method for changing the geometry of space by creating a wave that would cause the fabric of space ahead of a spacecraft to contract and the space behind it to expand (see [Alcubierre drive](#)). The ship would then ride this wave inside a region of flat space, known as a *warp bubble* and would not move within this bubble but instead be carried along as the region itself moves due to the actions of the drive.

In 1992 [Evgeny Podkletnov](#)^[250] published a heavily debated^{[251][252][253][254]} journal article claiming a specific type of rotating superconductor could shield gravitational force. Independently of this, from 1991 to 1993 [Ning Li](#) and Douglas Torr published a number of articles^{[255][256][257]} about gravitational effects in superconductors. One finding they derived is the source of [gravitomagnetic flux](#) in a [type II superconductor](#) material is due to [spin alignment](#) of the lattice ions. Quoting from their third paper: "It is shown that the coherent alignment of lattice ion spins will generate a detectable gravitomagnetic field, and in the presence of a time-dependent applied magnetic vector potential field, a detectable gravitoelectric field." The claimed size of the generated force has been disputed by some^{[258][259]} but defended by others.^{[260][261]} In 1997 Li published a paper attempting to replicate Podkletnov's results and showed the effect was very small, if it existed at all.^[262] Li is reported to have left the University of Alabama in 1999 to found the company *AC Gravity LLC*.^[263] *AC Gravity* was awarded a [U.S. Department of Defense](#) grant for \$448,970 in 2001 to continue anti-gravity research. The grant period ended in 2002 but no results from this research were made public.^[264]

In 2002 [Phantom Works](#), [Boeing's](#) advanced research and development facility in [Seattle](#), approached [Evgeny Podkletnov](#) directly. Phantom Works was blocked by Russian technology transfer controls. At this time Lieutenant General George Muellner, the outgoing head of the Boeing Phantom Works, confirmed that attempts by Boeing to work with Podkletnov had been blocked by Russian government, also commenting that "The physical principles – and Podkletnov's device is not the only one – appear to be valid... There is basic science there. They're not breaking the laws of physics. The issue is whether the science can be engineered into something workable"^[265]

Froning and Roach (2002)^[266] put forward a paper that builds on the work of Puthoff, Haisch and Alcubierre. They used fluid dynamic simulations to model the interaction of a vehicle (like that proposed by Alcubierre) with the zero-point field. Vacuum field perturbations are simulated by fluid field perturbations and the aerodynamic resistance of viscous drag exerted on the interior of the vehicle is compared to the Lorentz force exerted by the zero-point field (a Casimir-like force is exerted on the exterior by unbalanced zero-point radiation pressures). They find that the optimized negative energy required for an Alcubierre drive is where it is a saucer-shaped vehicle

with [toroidal](#) electromagnetic fields. The EM fields distort the vacuum field perturbations surrounding the craft sufficiently to affect the permeability and permittivity of space.

In 2009, Giorgio Fontana and Bernd Binder presented a new method to potentially extract the Zero-point energy of the electromagnetic field and nuclear forces in the form of [gravitational waves](#).^[267] In the spheron model of the nucleus,^[268] proposed by the two times Nobel laureate [Linus Pauling](#), [dineutrons](#) are among the components of this structure. Similarly to a [dumbbell](#) put in a [suitable rotational state](#), but with nuclear mass density, dineutrons are nearly ideal sources of gravitational waves at X-ray and gamma-ray frequencies. The dynamical interplay, mediated by nuclear forces, between the electrically neutral dineutrons and the electrically charged core nucleus is the fundamental mechanism by which nuclear vibrations can be converted to a rotational state of dineutrons with emission of gravitational waves. Gravity and gravitational waves are well described by General Relativity, that is not a quantum theory, this implies that there is no Zero-point energy for gravity in this theory, therefore dineutrons will emit gravitational waves like any other known source of gravitational waves. In Fontana and Binder paper, nuclear species with dynamical instabilities, related to the Zero-point energy of the electromagnetic field and nuclear forces, and possessing dineutrons, will emit gravitational waves. In experimental physics this approach is still unexplored.

In 2014 [NASA's Eagleworks](#) Laboratories announced that they had successfully validated the use of a [Quantum Vacuum Plasma Thruster](#) which makes use of the Casimir effect for propulsion.^{[269][270][271]} In 2016 a scientific paper by the team of NASA scientists passed peer review for the first time.^[272] The paper suggests that the zero-point field acts as [pilot-wave](#) and that the thrust may be due to particles pushing off the quantum vacuum. While peer review doesn't guarantee that a finding or observation is valid, it does indicate that independent scientists looked over the experimental setup, results, and interpretation and that they could not find any obvious errors in the methodology and that they found the results reasonable. In the paper, the authors identify and discuss nine potential sources of experimental errors, including rogue air currents, leaky electromagnetic radiation, and magnetic interactions. Not all of them could be completely ruled out, and further peer-reviewed experimentation is needed in order to rule these potential errors out.^[273]

Harnessing Zero-Point Energy

Submitted as coursework for [PH240](#), Stanford University, Fall 2017

Introduction

From the fictional universe of Stargate Atlantis and Marvel Comic's *Realm of Kings* to NASA's Eagleworks Propulsion laboratory, zero-point energy, also known as vacuum energy, is touted as a potentially limitless and ubiquitous source of energy, if one can only find the means to harness it. [1] Zero-point energy can be formulated in a few different ways, but in its most basic form, it is the minimal yet non-zero energy of a quantum mechanical system. In quantum field theory, zero-point energy can be considered by computing the expected energy of the zero photon mode. [2] In a system with no physical boundaries, the expected energy of the zero photon mode diverges! Yet, if this energy uniformly permeates all of space-time, it is not directly observable.

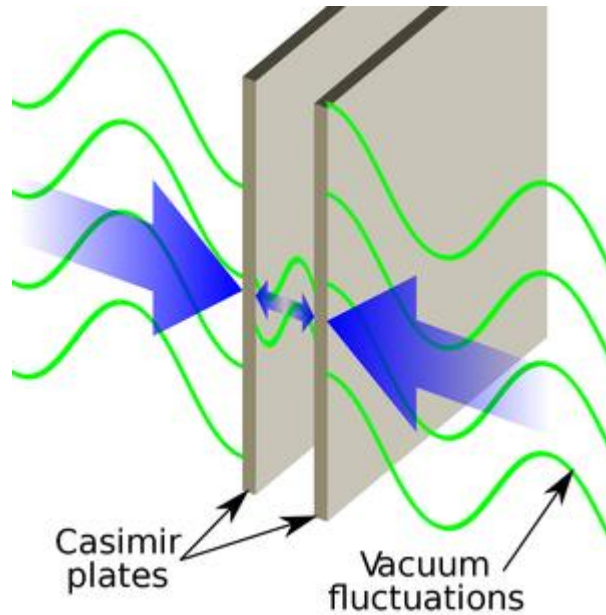


Fig. 1: Demonstration of the force resulting from discrepancies in the energies of vacuum states, and thus pressure exerted on boundaries.

Conceptual Framework

For pedagogical reasons, we will consider the popular formulation of zero-point energy. The most interesting and relevant framework for zero-point energy can be understood from the quantum field theory for photons and electrons: quantum electrodynamics. Glossing over an exceptional amount of mathematical and conceptual background, the energy of a state in quantum field theory is computed as an expectation of a Hamiltonian, $\langle H \rangle$, which describes the energy of the state in terms of operators acting on wavefunctions. The final computation usually requires an integral over the allowed momenta of particles in the state.

Following Schwartz, we can compute the energy of a zero-photon vacuum state with infinite boundaries, a system that is in no way physical, realizable or complete in its description, but pedagogical nonetheless. [2] Again glossing over much of the background information (which we encourage the interested reader to peruse in reference [2]), we find that, $E_{\text{vac}} = \langle H \rangle \propto \int k^3 dk \rightarrow \infty$. And thus we see that the expected energy of the vacuum state diverges! Of course this isn't truly a physical system as no other particles are present and there are no boundaries, but it illustrates the idea of energy present in empty space.

A Dutch physicist by the name of Hendrik Casimir took this formalism even farther and considered a slightly more physical system consisting of a conducting and hollow cube of side length L in vacuum. [3] Within this cube is a conducting square plate of side length L , parallel, and positioned in close proximity, to one of the sides of the cube. He then computed two energies: the energy of the zero-photon state, or electromagnetic vacuum state, in the region bounded by the two closely separated planes; and the energy of the vacuum state in the rest of the cube. The two quantities are different as the boundary conditions only allow certain modes, or standing waves, to exist in either region.

Formally, both energies are divergent, yet the difference between the two expressions is well-defined and can be manipulated to compute a force. Casimir interpreted this as an interaction between the closely separated plates and found that there is an attractive force that falls off sharply with separation. A cross-section of the geometry of the two plates and the resulting force is illustrated in Fig 1., where the force is given by the rather simple expression, $F = (\pi^2 \hbar c / 240 a^4) L^2$ for some separation a . Although the effect is exceptionally small, he predicted "an experimental confirmation seems not unfeasible and might be of a certain interest". [3]

This calculation ignores a significant number of things, such as physical properties of the metals constituting Casimir's box. However, different

materials, either metal or non-metal, simply change the coefficient of the computed force, while the dependence on separation and surface area remain the same.

Experimental Verification

So we've seen that there is a reasonable theoretical framework for the energy associated to electromagnetic vacuum states, and that certain electrode geometries can provide indirect means to observe these vacuum energies. One then might ask, has such a thing been experimentally verified. Although there was a dedicated measurement in 1958 by M. J. Sparnaay, he only found that his measurements did not contradict Casimir's prediction, and indeed they were far from precise. [4]

More recently, circa 1997, a physicist at the University of Washington made use of a torsion pendulum to measure the force between two conductors: one flat and the other hemispherical. [5] He found that at separations of less than 1 micron, there was a comparatively substantial force between the plates that was most readily explained by Casimir's predicted interaction. He took into account modifications to the force from the differing geometry, finite conductivity of real metals, and backgrounds due to both thermal and electrostatic effects. This was the first direct observation and statistically sound analysis to verify the force which Casimir had postulated almost 50 years before.

Since 1997, there has been a wealth of work dedicated to constraining some of the finer and more finicky details of the Casimir effect, as well as studies that have observed other phenomenon associated to vacuum energy, oft referred to as corollaries of the original Casimir effect. The interested reader might try investigating the plasma model vs. the Drude model or the Dynamical Casimir Effect.

The Ultimate Goal: Thrust Without Fuel

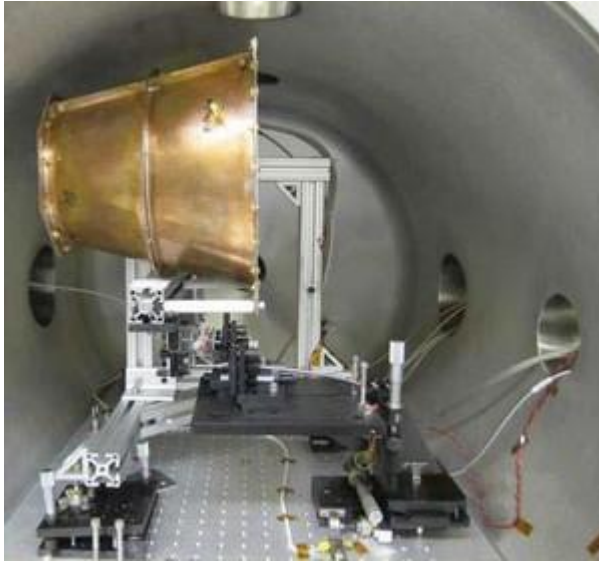


Fig. 2: Photograph of the thruster cavity (copper, left), its supporting structure and enclosing vacuum chamber (rear).

Measuring a force between two metal plates is all well and good (exceptional in fact), but the pragmatist might wonder what use could come of said measurement, or even the applicability of the driving theory itself. With this line of thinking, we finally return to our first reference: an alleged measurement of thrust from a "Casimir Rocket" at NASA's Eagleworks Laboratories. [1] By investigating the relatively new realm of observable consequences of quantum vacuum fluctuations, and making use of highly-skilled space-flight engineers, NASA hopes to construct a propulsion system that does not require a fuel, only energy in the form of electrical power.

To power rockets and provide thrust, current space-flight technologies depend almost entirely on the use of chemicals as fuels, including liquid oxygen, hydrazine, composite solid fuels, and many more. The most significant disadvantage of such a fuel is the fixed thrust to weight ratio. If you want more thrust, or thrust for a longer period of time, you need to bring more fuel. It would be much nicer if you could bring along a little solar-powered space engine, of fixed weight, and get it to push your spaceship around. But what would provide the thrust?

NASA's answer: quantum vacuum fluctuations. And thus Eagleworks was born. Their aim is to make use of complex and highly-specialized conducting cavities to generate a thrust that "pushes" against the vacuum of space by directing the flow of virtual electrons and positrons generated from a standing radio-frequency wave inside the closed cavity. If this were possible, all it would need is a little electricity and the only barrier between humankind and a future in the stars would be the time it takes to get anywhere.

In fact, Eagleworks has recently published a paper detailing a supposed, and exceedingly contentious, measurement of thrust from a prototype Electromagnetic (EM) Drive, depicted in Fig. 2. [1] Their initial 2014 test was not performed in vacuum, which led a number of opponents to claim the thrust was likely due to convection of heat induced by the source of the electromagnetic driving field. However, their recent publication involves a more precise measurement performed in vacuum, which can often be decidedly more conclusive. As with the Great Superluminal Scare of 2011, NASA's result requires extensive scrutiny and where possible, reproduction.

Opposition

As was mentioned before, this measurement of thrust generated by pushing against the vacuum of spacetime has significant opposition from the physics community, and rightly so. The most obvious issue is a simple violation of conservation of momentum. NASA has claimed to build a "thruster" which, in theory, can propel itself from rest without ejecting either matter or photons. Trivially, $p_{final} \neq p_{initial}$ which is a problem! Although unlikely, it is possible that the drive is generating thrust by ejecting some other type of weakly-interacting particle, maybe even through a mechanism not currently encoded by the Standard Model.

All physical arguments aside, the measurement claimed supposedly observes a thrust of 10s of micro-Newtons, with a slow (1/f) drift on the order of 100s of micro-Newtons. [1] Purely from a metrological

standpoint, this type of measurement is fraught with error, even using techniques to identify signals by their spectral properties. In time, it's possible that better measurements could be made.

Conclusions

Harnessing energy and thrust from the vacuum of space would be undeniably astounding, and is the main project goal at NASA's Eagleworks labs. Yet, such an idea must contend with physical laws like simple conservation of momentum and would benefit from a well-described mechanism, even if it's only an effective description.

Recently in 2017, vacuum fluctuations have allegedly been demonstrated to provide thrust in a prototype EM drive. This is preposterous measurement that is physically impossible, both from fundamental arguments and a metrological standpoint, as the brief discussion above demonstrated.

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Quantum Vacuum Engineering for Power and Propulsion from the
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Abstract. This talk describes challenges and possibilities for exploiting the stupendous energetics that may be contained within the zero-point ground state of seemingly “empty” space for meeting Earth's future power and propulsion needs. In particular, it's suggested that intense vacuum energetics, in addition to those that reside within the vacuum's more well known electromagnetic modes, and research on specially conditioned electromagnetic radiation to interact with these energetic modes is described. And, in addition to its energy, it is shown that quantum vacuum negative pressure could conceivably enable less labored vehicle motion in it.

INTRODUCTION The most bizarre possibility for meeting Earth's power and propulsion needs may be the harvesting the stupendous energetics that possibly exist within the quantum mechanical ground states of the vacuum of “empty” space. These energetics are symbolized in Figure 1 as electromagnetic pulsations that - like lightening flashes – forever appear and disappear throughout the entire cosmos in countless times and places. The more simple interpretations of quantum theory predict that quantum fluctuations in the vacuum state of space give rise to energy fluctuations whose average expectation values could be 40-100 orders of magnitude greater than all of the energy contained in cosmic matter. Wheeler, 1968 speculates that the enormous vigor and vitality within the submicroscopic intensity of individual vacuum energy fluctuations is diminished by some sort of wave interference-like effect that almost totally diminishes their intensity over the much larger scales of time and distance that unaided senses can perceive. So, space is inert and empty to ordinary observation. But Figure 1 shows that zero-point energy densities of 1.0 J/cm^3 to $10,000 \text{ J/cm}^3$ would be revealed to hypothetical probes that could sense and resolve

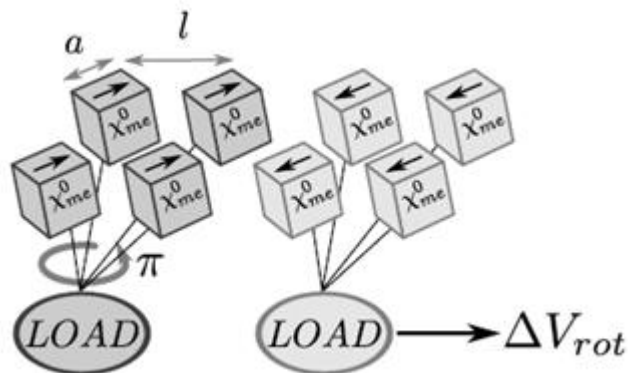
physical activity occurring over 10^{-6} cm 10^{-7} cm scales of distance. And at 10^{-7} cm scales, much more violent 10^3 J/ cm³ activity would be perceived. Figure 1 Expectation Values of Zero-Point Energy in 10^{-6} and 10^{-7} cm. Regions within the Quantum Vacuum of Space

*Copyright: September 2009 by H.D. Froning Jr. Presented at Third International Conference on Future Energy Washington Hilton Hotel,

A Blueprint for a Quantum Propulsion Machine

Push on the electromagnetic fields in the quantum vacuum and you should get an equal and opposite force.

The quantum vacuum has fascinated physicists ever since Hendrik Casimir and Dirk Polder suggested in 1948 that it would exert a force on a pair of narrowly separated conducting plates. Their idea was eventually confirmed when the force was measured in 1997. Just how to exploit this force is still not clear, however.



In recent years, a new way of thinking about the quantum vacuum has emerged which has vastly more potential. And today, one physicist describes how it could be used to create propulsion.

Before we discuss that, let's track back a little. According to quantum mechanics, any vacuum will be filled with electromagnetic waves leaping in and out of existence. It turns out that these waves can have various measurable effects, such as the Casimir-Polder force.

The new approach focuses on the momentum associated with these electromagnetic fields rather than the force they exert. The question is whether it is possible to modify this momentum because, if you can, you

should receive an equal and opposite kick. That's what rocket scientists call propulsion.

Today, Alex Feigel at the Soreq Nuclear Research Center, a government lab in Yavne Israel, suggests an entirely new way to modify the momentum of the quantum vacuum and how this can be exploited to generate propulsion.

Feigel's approach combines two well-established ideas. The first is the Lorentz force experienced by a charged particle in electric and magnetic fields that are crossed. The second is the magnetoelectric effect—the phenomenon in which an external magnetic field induces a polarised internal electric field in certain materials and vice versa.

The question that Feigel asks is in what circumstances the electromagnetic fields in a quantum vacuum can exert a Lorentz force. The answer is that the quantum vacuum constantly interacts with magnetoelectric materials generating Lorentz forces. Most of the time, however, these forces sum to zero.

However, Feigel says there are four cases in which the forces do not sum to zero. Two of these are already known, for example confining the quantum field between two plates, which excludes longer wavelength waves.

But Feigel says the two others offer entirely new ways to exploit the quantum vacuum using magnetoelectric nanoparticles to interact with the electromagnetic fields it contains.

The first method is to rapidly aggregate a number of magnetoelectric nanoparticles, a process which influences the boundary conditions for higher frequency electromagnetic waves, generating a force.

The second is simply to rotate a group of magnetoelectric nanoparticles, which also generates a Lorentz force.

Either way, the result is a change in velocity. As Feigel puts it: “mechanical action of quantum vacuum on magneto-electric objects may be observable and have a significant value.”

The beauty of Feigel’s idea is that it can be easily tested. He suggests building an addressable array of magnetoelectric nanoparticles, perhaps made of a material such as FeGaO₃ which has a magnetoelectric constant of 10^{-4} in a weak magnetic field.

These nanoparticles simply have to be rotated in the required way to generate a force. Feigel calls it a magnetoelectric quantum wheel.

Of course, nobody is getting a free lunch here. “Although the proposed engine will consume energy for manipulation of the particles, the propulsion will occur without any loss of mass,” says Feigel. He even suggests, with masterful understatement, that this might have practical implications.

So here is a high-risk idea with a huge potential payoff. The question is: who has the balls to try it?

SPECIAL ACCESS PROGRAMS

The three-tier standard government security clearance levels are well known: confidential, secret and top secret.

However just having a clearance at one of these levels does not automatically give access to any information at that level. There has to be a demonstrable “need to know” in order to be briefed or read in on a given project, program, facility or intelligence product. But this system is merely the “white” side of the security system. There is a massive secret “black” system as well, the existence of which is known while the details (naturally) are deeply hidden. (For a publicly available overview see the [Report of the Commission on Protecting and Reducing Government Secrecy: 1997](#), chaired by Sen. Daniel Patrick Moynihan, Senate Document 105-2. See also the report [In Search of the Pentagon’s billion dollar hidden budgets](#) by Bill Sweetman, North American editor for the British publication Jane’s Defence Weekly, from which much of the following material has been condensed.) This structure has been described as a “shadow military” existing in parallel with open or overtly classified programs. It is for programs considered to be too sensitive for normal classification measures: these are called Special Access Programs (SAPs). They are protected by a security system of great complexity. Many of the SAPs are located within industry funded through special contracts. Under arrangements called “carve-outs” such programs and funds become removed from the usual security and contract-oversight organizations. In 1997 there were at least 150 SAPs.

There are also levels of SAP, the first being a division into acknowledged and unacknowledged SAPs. Black Program is slang for an unacknowledged SAP. An unacknowledged SAP is so sensitive that its very existence is a “core secret.” Indeed, some unacknowledged SAPs are

sensitive to the extent that they are “waived” (a technical term) from the normal management and oversight protocols. Even members of Congress on appropriations committees (the Senate and House committees that allocate budgets) and intelligence committees are not allowed to know anything about these programs. In the case of a waived SAP, only eight members of Congress (the chairs and ranking minority members of the four defense committees) are even notified that a given program has been waived (without being told anything about the nature of the program). Such a program is certainly deep black (though I am not sure if that designation is actually used in the business).

The number of people with access to multiple SAPs is deliberately very limited. This virtually assures that hardly anyone knows what is going on in another program. Black programs are often covered by white (normal classification system) or unclassified programs. The U2 spyplane was covered by a weather-research aircraft program. Such covering allows technology to be relatively openly developed until such time as it is ready for application to a black program. The overt cover program is then usually cancelled, having accomplished its purpose. This happened to the X-30 National Aerospaceplane project in 1994. It appeared to be an unrealistically ambitious program that was eventually cancelled, but was in reality a cover for what is almost certainly a black-world hypersonic aircraft according to defense analyst Sweetman. (This may be the source of the phantom sonic boom phenomenon reported since the early 1990s.)

Someone read in on an unacknowledged SAP would be required to deny even its existence, i.e. even a "no comment" would be a serious breach of security. It can also happen that someone, such as a general or admiral, ostensibly responsible for certain types of programs or areas of technology would not be briefed on the existence of a program that should be within his jurisdiction. (If your name is not on the so-called "bigot list" for a program you will not be briefed, no matter what your rank or responsibility. Even the director of the CIA or the DIA would not ex officio and automatically be on all such lists.) The wall of denial in the deep black world can thus be maintained by both deception and deliberately designed lack of cognizance leading to apparently honest denial. In addition to passive security, active measures can also be deemed necessary: disinformation. Again according to the report by Sweetman, two high level commissions have concluded that, among other things, black programs include "systematic efforts to confuse and disinform the public." One disinformation ploy is to divulge both real and fabricated information of equal apparent credibility mixed together to someone or some group. The fabricated information can then be used to discredit claims, individuals or organizations. This is a highly effective way to keep a major secret: let the secret be revealed but mixed with sufficient disinformation to assure that the secret will not be believed by anyone who actually matters, for example the national media. The cost of such intense levels of security can be quite steep. It has been estimated that an intensively sensitive program may consume half or even more of its secret budget in security.

The products of the intelligence community are termed Sensitive Compartmented Information (SCI). It is easier to keep a program hidden in a contractor facility than in a government facility. Deeply buried programs in contractor facilities are called "carve outs" (referring to the budget). A crash retrieval or some classified continuation of Project Blue Book would likely exist as a deep black industrially-based SAP. A program involving hardware would be considered technology rather than intelligence and most likely fall under the office of the Under Secretary of Defense for Acquisition, Technology and Logistics. Ironically for such a program even someone having an intelligence "ticket" at the highest level would not be considered to have a need to know. All of this results in very effective isolation and virtually no one in a position of open civilian governmental authority being cognizant of this after a time, even though, at least in principle, the Special Access Program Oversight Committee, SAPOC, should be cognizant of such a program. I do not know of any fundamentally limiting factors in the potential longevity of a program. The extreme compartmentalization and limited oversight would tend to keep a program in existence, perhaps indefinitely. Political leaders come and go, pandering to the masses for votes in the eyes of many within the military and intelligence communities, and as a result have varying degrees of respect and trust in that world. Deep black programs can become quite independent of any given administration, and it would certainly be unrealistic to assume that a given president has been briefed on every SAP. A president does not automatically have a need to know. (See [Would the President be Briefed on a UFO Special Access Program](#); also [Some](#)

[Thoughts on Keeping It Secret.](#)) Moreover Freedom of Information Act requests cannot penetrate unacknowledged special access programs.

The 15 U.S. Aerospace Crafts Built with Extraterrestrial Technology

by
Richard Boylan, Ph.D.

At this time, Dr. Boylan is aware of the existence of 15 kinds of exotic-technology *human-constructed* antigravity aerospace crafts, all incorporating extraterrestrially-derived gravity-shielding (reduced-gravity) or full antigravity technology.

These 15 vehicles are: 1) the Northrop Grumman B-2 Spirit Stealth Bomber, 2) the F-22 Raptor advanced Stealth Fighter, 3) its successor, the F-35 Lightning II advanced Stealth Fighter; 4) Lockheed-Martin SR-72 'Dark Star' ISR hypersonic Bomber; 5) Northrop-Grumman TR3-B 'Black Manta' Triangle ship; 6) Lockheed-Martin's X-33A wedge-shaped space fighter; 7) the Northrop-Grumman Pumpkinseed aerospace craft; 8) Northrop-Grumman's 'Great Pumpkin' antigravity disc fighter [official designation unknown]; 9) the Boeing X-22A two-man antigravity disc; 10) Teledyne-Ryan/Northrop-Grumman XH-75D Shark antigravity helicopter; 11) Northrop-Grumman TR3-A 'Astra' Triangle anti-gravity spacecraft; 12) Northrop-Grumman's Quantum Teleportation Disc; 13) Michelson Laboratory-CLNWRS Hydro Aerospace/Underwater Craft/HAUC , (better known as the TIC-TAC); 14) Lockheed-Boeing-Airbus Industries Nautilus Deep-Space Ship, (Earth's only interstellar spaceship; and 15) Boeing X-37C Crewed Tactical~Strategic Astronautical Combat Cruiser.

A total of 15 reduced-gravity aeronautical and fully-antigravity astronautical crafts are now known to exist. They are listed below.

It took the U.S. 45 years to figure out (with extraterrestrial consultants' help) how a UFO flies, but the U.S. finally got it up! All of these technologies are primitive in comparison with the Star Visitors' own spacecrafts, which utilize not only artificial internally-generated gravity fields which eliminate weight and inertia, but can also harness a range of quantum effects to 'short-cut' through space. Let us now examine in more detail **these 15 advanced Human-built antigravity crafts**. The amount of information available for each varies; in some cases more is known, in other cases very little.

1) The B-2 Stealth Bomber is manufactured by Northrop-Grumman. The Air Force describes it as a low-observable, strategic, long-range heavy bomber capable of penetrating sophisticated and dense air-defense shields. The Stealth Bomber has navigation and guidance systems directed by a classified Artificial Intelligence (AI) program. This AI is exotic, involving the connecting together PCR-cloned copies of extraterrestrial brain tissue with advanced integrated circuits to fashion hybrid sentient 'neuro chips'. The B-2 gets extra lift in-flight by the turning on its electro-gravitic fields along its wings and fuselage to considerably neutralize the pull of gravity. Now you begin to see why the U.S.'s Northrop B-2s cost about a billion dollars each. (3.)

2) The F-22 Raptor advanced Stealth Fighter is built by a joint effort of the Lockheed-Martin Skunk Works and Boeing's Phantom Works. In crude imitation of extraterrestrial starcraft, the guidance system of this F-22 aircraft incorporates special (AI), Artificial Intelligence, meaning that cloned nerve pathways patterned on Star Visitor brain tissues are incorporated into the semi-sentient and semi-autonomously-functioning guidance system integrated with the aircraft. In addition, the F-22 has antigravity weight-reduction capability, which is exercised selectively by the pilot who is in mental connection with the AI guidance system, which activates the antigravity field generation as needed in coordination with the F-22's conventional jet engine thrust to effect the overall maneuvering of the F-22 Raptor. Dr. Boylan has personally witnessed a F-22 Stealth Fighter pull up at an Air Show and hover

vertically on its tail in mid-air for over two minutes, dancing slowly, and gently rotating about on its vertical axis with little regard for the pull of gravity! Hats off to the woman Marine Air Major driving that Stealth Fighter!

3) The F-35 Lightning II (5th gen.) Stealth Fighter is built jointly by Lockheed-Martin, Northrop-Grumman and BAE. The F-35 *similarly* incorporates quasi-sentient Artificial Intelligence and antigravity weight-reduction technology (retrieved and back-engineered from Star Visitor technologies) in addition to its jet thrust.

4) The Lockheed-Martin SR-72 'DARK STAR' 6th-Gen., 4600 mph, HYPERSONIC, HIGHLY-GRAVITY-SHIELDED STEALTH BOMBER. This coyly semi-announced-as-operational ultrasteamlined advanced aerospace vehicle is the first *6th-Generation* stealth, hypersonic, surveillance-reconnaissance-strategic bomber. (It was briefly shown taking off at the finale of the Tom Cruise *Top Gun II* movie.) It has enormous range, extreme speed, and low visibility, because it is gravity-shielded.

5) Northrop-Grumman's TR3-B 'Black Manta' , is the smaller version of its big brother, the TR3-A 'Astra' spacecraft , a triangular anti-gravity ship within the U.S.S.F.'s Solar Warden Space Fleet. The TR3-B's existence was revealed by defense industry Black-Projects insider Edgar Rothschild Fouche in his book *Alien Rapture*. The TR3-B does not depend solely or principally on its hydrogen-oxygen rockets. It is a highly gravity-reduced aerospace craft manufactured in a secret "black program" by Boeing Phantom Works adjacent to Area 51. The reduced-gravity field it produces reduces the vehicle's weight by about 90% so that very little thrust is required to either keep it aloft or to propel it, (at speeds of Mach 9 or higher). The TR3-B vehicle's outer coating is electrochemical-reactive and changes with electrical radio-frequency radar stimulation, and can change reflectiveness, radar absorptiveness, and color. This is also the first US vehicle to use quasi-crystals in the vehicle's skin. This polymer

skin, when used in conjunction with the TR-3B's Electronic Counter Measures and Electronic Counter-Countermeasures (ECCM), can make the vehicle look like a small aircraft, or a flying cylinder - or even trick radar receivers into falsely detecting a variety of aircraft, no aircraft, or several false aircraft at various locations!

A circular plasma-filled accelerator ring called the Magnetic Field Disrupter [MFD] surrounds the rotatable crew compartment inside the TR3-B, and is far ahead of any imaginable technology. U.S. Sandia and Livermore National Laboratories developed the reverse-engineered MFD technology. The mercury-based plasma is pressurized at 250,000 atmospheres at a temperature of 150 degrees Kelvin, and accelerated to 50,000 rpm to create a super-conductive charged plasma with resulting gravity-disruption [reduction of almost all of the pull of gravity and effects of inertia].

The MFD generates a magnetic-vortex field which disrupts or neutralizes the effects of gravity by 99% on any mass, e.g. crew within the field. The MFD creates a disruption of the Earth's gravitational field upon the mass within the circular accelerator. The mass of the circular accelerator and all mass within the accelerator, such as the crew capsule, avionics, MFD systems, fuels, crew environmental systems, and the nuclear reactor, are reduced by 99%. The current MFD in the TR-3B craft causes the effect of making the vehicle extremely light, and able to outperform and outmaneuver any craft yet constructed - except of course those back-engineered, 100%-antigravity crafts which the government does not admit exist, but does have.

The TR3-B is a high-altitude stealth reconnaissance platform with an indefinite loiter time. Once it gets to operational altitude, it doesn't require much propulsion to maintain its altitude. With the vehicle mass reduced by over 99%, the craft can travel at Mach 9 vertically or horizontally. Because the effect of Earth's gravity is largely nullified by the secondary gravitational field aboard, inertia is virtually absent, and the extreme speeds produced cause no bodily stress on the crew on board.

The TR3-B propulsion is provided by three multimode thrusters mounted at each bottom corner of the triangular platform. The TR-3 is a

sub-Mach 9 vehicle *until* it reaches altitudes above 120,000 feet - then, above atmospheric drag, it can go way faster!

The reactor heats the liquid hydrogen and injects liquid oxygen into the supersonic nozzle, so that the hydrogen burns concurrently in the liquid-oxygen afterburner. The multimode propulsion system can operate in the atmosphere with lift from the Magnetic Field Disrupter powered by the nuclear reactor - which creates a secondary gravity field enveloping the craft, nullifying Earth's gravity pull, and then provides principal propulsion of the craft in space by manipulating its internal gravity field's polarity (its attraction or repellancy modes). For fine-tuned changes to the craft's position in space, it uses the three thrusters, which create propulsion by burning the combined hydrogen/oxygen fuels

6) Lockheed-Martin X-33A. While Lockheed openly acknowledges the existence of its National Space Plane, the rocket-engineered X-33 [no -A] 'prototype', a single-stage-to-orbit reusable aerospace vehicle, Lockheed's *other* secret space plane, the X-33A incorporates full antigravity technology. Lockheed-Martin does not say too much about its conventional winged delta-shape X-33 VentureStar except to say that 'we are in the process of building it.' When Lockheed says that about about a long-stalled sensitive program, it is clear that Lockheed-Martin is using the National Space Plane program to hide its already-operational classified *antigravity* military version, which I have dubbed the **X-33A**. (The 'A' suffix stands for antigravity.) Colonel Donald Ware, USAF (ret.) told Dr. Boylan that he had recently learned from a three-star General that the "VentureStar X-33" has an electrogravitics system on board(6.). This means that the admitted X-33 Space Plane has weak gravity-reducing technology incorporated. But the unacknowledged X-33A spacecraft *is fully antigravity*.

7) Northrop-Grumman TR3-A 'Pumpkinseed' is a super-fast air vehicle. The 'Pumpkinseed' nickname is a reference to its thin oval airframe whose contours resemble that seed. It is the craft identified as using Pulse-Detonation Wave Engine (PDWE) technology for propulsion in a sub-hypersonic regime. The Pumpkinseed then uses

antigravity technology for reducing the vehicle's mass and for field propulsion at higher altitude and speed levels. As air breathers, these Pulse Detonation Wave Engines can propel a hypersonic aircraft towards Mach 10 at an altitude in excess of 180,000 feet. When used to power an trans-atmospheric vehicle, the same PDWEs are capable of lifting the craft to the edge of space when switched to rocket mode.

8) Northrop-Grumman 'GREAT PUMPKIN' Antigravity Disc Fighter, (official designation not known_, dubbed 'the Great Pumpkin' by Dr. Boylan for its brilliant-orangish plasma glow when energized.) It is manufactured by Northrop Grumman Advanced Concepts and Technologies Division, Palmdale, CA. Dr. Boylan first saw these craft test-flown in 1992 above the Groom Mountains Range ridgeline at Area 51, Nevada. Later he saw the same intense burning-bright orange-gold craft that he had seen above Area 51, NV being test-flown at Northrop's installation inside Tehachapi Mountain, northwest of Edwards Air Force Base, sixty miles north of Los Angeles. There Northrop has its secret saucer manufacturing works buried deep inside the Mountain. Dr. Boylan later saw the self-same intense burning-bright orange-gold craft test-flown above the Northrop-Grumman Plant ridge-top test at Tehachapi Mountain, Palmdale as he had seen flown above Area 51. When energized, these discs emit their blindingly-intense glow. It is reasonable to assume that this is due to strong ionization of the surrounding air, and that electrogravitics is part of the methodology of their field propulsion.

9) Boeing X-22A, two-man antigravity disc fighter. The late Colonel Steve Wilson, USAF stated that military astronauts trained at a secret aerospace academy adjacent to but separate underground from the regular Air Force Academy at Colorado Springs, CO. These military astronauts then operate out of Beale and Vandenberg Air Force Bases, Northern California. From those bases, these military astronauts regularly fly trans-atmospherically and out into deep space (7). The late Colonel Steve Wilson confirmed that one of the aerospace craft these astronauts fly is that X-22A. Another informant told Dr. Boylan that the

Boeing X-22A antigravity disc is capable of achieving optical as well as radar invisibility! (8).

Recently Dr. Boylan also heard from an Army engineer, formerly TDY'ed to NASA and who shall remain unnamed at his request. He also confirmed that Lockheed had made the X-22A, the two-man antigravity disc which Dr. Boylan had seen test-flown in a Tonopah Test Range canyon west of the main Area 51 operations area. The engineer explained why Dr. Boylan had seen the X-22A flown so gingerly during that test flight. The engineer said that the original X-22A had had a standard altimeter hard-wired into it, but that such an instrument would give faulty readings sitting in the middle of the craft's antigravity field (which bends space&time.) He had recommended that they instead use a gradiometer, which would function better. Apparently his suggestion was finally taken up, since in more recent years Dr. Boylan has seen the X-22A again flown more smoothly and confidently and at higher altitudes over and near Area 51.

10) The Teledyne-Ryan/Northrop-Grumman XH-75D (or XH Shark) antigravity helicopter was manufactured by Teledyne Ryan Aeronautical Corporation of San Diego, (since bought out by Northrop-Grumman, who continues making updated versions). USAF Colonel Steve Wilson first told Dr. Boylan of the existence of this craft, and reported that many of these XH-75Ds were assigned to the National Reconnaissance Organization Delta Division which retrieves downed UFOs. Rogue elements within that Division, controlled by the Cabal, are also implicated in mutilating cattle as a psychological-warfare program on the American public to try to get citizens riled up to fear and hate ETs by assuming that 'aliens' in UFO antigravity crafta are the ones cutting up their cattle. The XH-75D was also obtained and used by the Cabal for MILABS kidnappings of innocent civilians, who are drugged, hypnotized, and flown off in these silent antigravity craft and given the impression that they are aboard a "flying saucer". (See photo of a disabled XH-75D antigravity helicopter being towed back to base at: http://media.tumblr.com/tumblr_lma7jquQmC1qijd42.jpg)

Of particular note is that the basic antigravity powering design of the XH-75D Shark, (compact nuclear fusion reactor powering an antigravity field generator), is basically the same platform used for the *Marine One Presidential & White House Dignitaries helicopter fleet*. These Marine Ones also have rotors propelled with functioning turbine engines to make noise and disguise the fact that silent antigravity technology is at work on board. The antigravity field also protects against crashes in the event of rotor failure, and also provides a repellent force-field against incoming missiles, etc.

11) The TR3-A 'Astra' spaceship, built by the Northrop-Grumman, is the larger triangular space-faring version of the TR3-B intra-atmosphere craft. The TR3-A 'Astra' is built to traverse deep space, and *can operate at an interplanetary level as needed*.

(12) *Northrop Quantum Teleportation Disc*. Do the above antigravity-field propulsion craft constitute the current state-of-the-art in advanced aerospace craft? No. There have been advances beyond 'mere' antigravity field propulsion. Quantum physics is now being harnessed to revolutionize several aerospace craft, and their lift, propulsion, and guidance systems. On a Sept. 16, 2005 field trip to the northeast boundary of Area 51, during a middle-of-the-night observation on a hill overlooking Area 51, Dr. Boylan saw first one, then another, and finally six brightly-glowing objects suddenly appear at approximately 1000' (305 meters) altitude over the desert floor. The intensely-glowing, ruddy, golden-orangish ionization field surrounding these crafts appeared similar to the bright electromagnetic-ionization field seen around the Northrop Antigravity Disc. But in the 13 years since Dr. Boylan had last observed those Northrop discs above Area 51, and at their Tehachapi Mountains manufacturing site, *considerable progress has been made!* In 1992 a Northrop Antigravity Disc could slowly rise vertically from its flight pad and gradually reached flight altitude. But **in 2005, the Northrop Grumman Quantum Teleportation Disc was**

able to instantly wink out [depart] from its flight pad and suddenly appear miles away at operational flight altitude without any visible approach being seen previously. It is not a matter of the ionization field having been turned off during approach for stealth purposes. The ionization field accompanies the electrogravitic field propulsion. If the ionization were turned off, the craft would have lost lift and fallen from the sky. Rather what appears to be the case is that **Northrop-Grumman engineers have incorporated quantum-physics principles into the Disc's lift and propulsion.** Simply stated, Northrop appears to have **harnessed Quantum properties of Entanglement, and Non-Locality, to achieve Quantum Teleportation of a man-made 'UFO'.** To an observer, the craft appears to have simply 'ceased to exist' on the flight pad, and then instantly 'become visible' several miles away at, say, 3000 feet altitude. If this interpretation of my observation is correct, then there exists a new entry in the U.S. antigravity fleet: **the Northrop Grumman Quantum-Entanglement Teleportation Disc !** If Black-Budget engineers keep using Quantum Technology to refine antigravity vehicles, we can foresee the day when a fleet of antigravity Quantum Teleportation Bombers on a U.S. Navy aircraft carrier suddenly wink out of sight on the carrier deck and, seconds later, suddenly reappear halfway around the globe at 35,000 feet altitude over an enemy target installation, using Quantum Physics principles of Non-Locality and Entanglement. The future is full of surprises! It seems this future is shaping up to be such a one.

13) Hydro Aerospace/Underwater Craft (HAUC), aka 'TIC-TAC', is *designed* at Michelson Laboratory (Naval Air Weapons Station China Lake) and *actually built* at Air Force Plant 42, Palmdale, CA. **The HAUC utilizes an autonomous gravity field-generating Magnetic Field Disruptor, MFD, (which received US patent 10144532B2.)** These HAUCs are the so-called 'TIC-TAC' spacecraft which Navy fighter jets' gun cameras have been videotaping and showing on TV news. The radical propulsion, lift, and maneuverability of these TIC-TACs are made possible thanks to an incredibly powerful

electromagnetic field that essentially creates a Quantum Vacuum State surrounding the HAUC/TIC-TAC. This allows the TIC-TAC to ignore aerodynamic or hydrodynamic forces and rapidly plow through the air or sea without inertial mass. This is key to the abilities of this hybrid craft to speed effortlessly through air, water, and space at incredible speeds with virtually no resistance in air or water, nor from inertia, nor from Earth's gravity.

The Hydro Aerospace/Underwater Craft is equally operational at the bottom of the sea, on a water surface, in the air, and in space. Multi-modal functioning is designed to make it a most versatile anti-gravity craft. With its range of operation, it can engage any opponent and evade them by instantly moving to another location, or to a Quantum Non-Locality Domain, as necessary. **The HAUC CYLINDER is a Joint Star Nations-Human spacecraft. The HAUC's CREW OF 7 IS INTERSTELLAR-INTEGRATED! with 2 Cosmonauts from Altair Aquila star system and 5 US Navy/Marine Aviator Astronauts.** The Altairians help not only with navigation and steering, but by utilizing the Quantum Vacuum State which the HAUC generates to give the craft antigravity lift, rapid propulsion, and no resistance in water or air. The Altairians as a people seek to avoid violence. Between the surrounding Quantum Vacuum State, and the uncertainties of the HAUC's location and physical domain of operation, and the speed the HAUC operates at, the Altairians' tactical-defense theory is: 'if you can't keep up with us, you can't shoot us.' :-) The Altairians have mastered *the defensive applications* of utilizing the Quantum Vacuum/Zero Point Energy Field which the HAUC generates so that they have no need for physical kinetic weapons like lasers or cannons.

The HAUC's operating range is from Earth's sea bed to the Moon or Mars. **The HAUC's technology has been awarded a U.S. Patent: US10144532B2: 'Craft Using an Inertial Mass Reduction Device.'** That Patent describes "a craft using an inertial mass reduction device comprised of an inner resonant cavity wall, an outer resonant cavity, and microwave emitters. The microwave emitters create high-frequency electromagnetic waves throughout the resonant cavity causing the resonant cavity to vibrate in an accelerated mode and *create a local*

polarized vacuum energy [quantum] state, exhibiting repulsive gravity [that repels Earth's gravity] outside the outer resonant cavity wall.â€• Yes, ET tech made it through the U.S. Patent Office. (With a Navy Admiral smoothing flustered feathers of Patent Office clerks. The HAUCs/TIC-TACs are designed at the Navy's elite Michelson Laboratory at Naval Air Weapons Station China Lake, CA incorporating ET-tech and using extraterrestrial consultants, and that engineering design is then manufactured at Air Force Plant 42, 90 miles southwest in Palmdale, CA.

The 'Solar Warden' USSF Space Fleet of the U.S. Navy/Marine Corps Space Commands and Allies currently has 37 HAUC/'TIC-TAC' CYLINDERS antigravity crafts.

14) The Nautilus Deep Space Ship, made by **Boeing-Lockheed-Airbus Consortium** is a very large, extremely-classified fully-antigravity deep-space vessel built to travel across our solar system and between the stars. It is the only one of the fifteen U.S. antigravity crafts engineered to be able to leave our solar system altogether and travel interstellar. The Nautilus's Deep Space capability is what Dr. Ben Rich, the head of Lockheed Martin's Advanced-Projects 'Skunk Works' meant when, in a 1993 speech to UCLA Alumni, he stated, "We already have the means to travel among the stars, but these technologies are locked up in Black Projects." The Nautilus is shaped like an enormous rounded metal cylinder, a giant silver cigar 1000 yards (meters) long by 300 yards in diameter. Containing interstellar-travel technology, the Nautilus is extremely expensive to manufacture. Price tag: \$870 billion dollars per copy. Only one has been built. The Nautilus is manufactured jointly by Boeing's Phantom Works, Lockheed-Martin's Advanced Developments Programs, and the Anglo-French-EU consortium Airbus Industries. It is assembled at the sprawling underground facilities beneath Area 52, the Tonopah Test Range west of Area 51 on the Nevada National Security Site, Nevada. A retired top Boeing executive confirmed to Dr. Boylan that Boeing's Phantom Works had teamed up with Europe's Airbus Industries to help manufacture the Nautilus secret

spaceship. The Nautilus operates clandestinely out of underground hangers built within Mount Barrow on the highly-restricted Marine Corps Chocolate Mountain Aerial Gunnery Range 35 miles east of Brawley and the Salton Sea, CA.

Unlike other antigravity craft, the Nautilus is not operated only by U.S. armed services, but rather in joint partnership of NASA, America's Space Agency with ESA, the European Space Agency. At Star Nations' insistence, Nautilus is restricted to peaceful uses only, and can only undertake a visit to other solar systems with explicit prior permission of Star Nations Alliance, our Milky Way Galaxy's official government.

15) Boeing X-37C CREWED

TACTICAL~STRATEGIC ASTRONAUTICAL COMBAT

CRUISER is Antigravity-Enveloped~Enabled, equipped with Omni-Directional Neutral Particle-Beam Cannons and High-Intensity Lasers, Invisibility Cloaking, and with Teleporting and Space-Time Altering capabilities. Crew is six Astronauts/Space Marines of the Navy and Marine Corps Space Commands. The X-37C Cruiser **engages in classified Solar Warden Space Fleet missions** including Intelligence, Surveillance, and Reconnaissance activity, transportation, resupply, as well as protection of U.S.'s Moon and Mars Bases. Science Applications International Corporation (SAIC) provided design collaboration on the X-37C Cruiser, which was then built by Boeing Defense, Space & Security division.

The Physics and Advanced Technology Behind U.S.-Made Antigravity Aerospace Vehicles.

Antigravity. There are *three* ways to create a super-powerful electromagnetic field, or create an alternative localized gravitational field, so as to reduce, or negate, Earth's gravitational attraction on an aeronautical or astronautical craft.

1. The first and most primitive antigravity technology is **electrogravitic** . This involves using voltages in the millions of volts

to disrupt the hold of Earth's gravitational field. One such electrogravitic technology results in an 89% reduction in gravity's hold on airframes in such vehicles as the B-2 Stealth Bomber. And given the intensely-bright ambient ionization field which Dr. Boylan saw around the X-22A antigravity disc test-flying adjacent to the Tonopah Test Range, Nevada, it is reasonable to assume that an extreme-voltage electromagnetic field was generated from within this craft.

2. The second level up of sophistication is **magneto-gravitic**. This involves generating high-energy toroidal fields spun at incredibly-high RPMs (e.g. 20,000 rpms), which also disrupts Earth's ambient gravitational field to the extent that a gravitational field counter-force is generated, independent of Earth's gravitational field. The early British black-programs aeronautical engineers called this 'dynamic counterbary'. A U.S. defense contractor, Edgar R. Fouche, who worked in 'black projects' revealed that the TR3-B Astra triangular craft achieves its silent floating ability and antigravity field propulsion by using this magneto-gravitic technology.

3. The third level of sophistication is **nucleo-gravitic**, the technology used in the very most modern U.S. antigravity crafts. This involves the direct harnessing of the inside-the-atomic-nucleus gravitons (gravitational force-carrier bosons) to create a second gravitational field surrounding an antigravity craft. This neutralizes Earth's natural gravitational-field pull on that craft, and generates its own custom, opposite-polarity gravitational field with which to navigate.

Two elements, Bismuth (Element 83) and Muscovium (Element 115), have unique gravitational characteristics because of their particular *unique atomic nucleus configuration*. Both have the 'Magic Number' of 184 neutrons in their atomic nucleus) in addition to their respective 83 or 115 protons. In Element 83, and in one special isotope variant of Element 115, the Strong Force Field naturally extends slightly outside their atomic nucleus. This Strong Force extension is greater and more potent in the variant-isotope Element 115 (Muscovium) than in

Element 83 (Bismuth).

The 'Magic Isotope' of Muscovium (Element 115) is stable and generates its own (*second*) gravitational field, independent of, and by opposite polarity, repellant to Earth's gravitational field. Amplifying that second gravitational field created by the Element 115 isotope's Strong Force graviton bosons creates an independent *second* gravitational force field which GE scientist Henry W. Wallace called a "kinemassic-field body", [kine (force) + mass (amount of matter in an object)] This field suffuses the craft body's mass with an integrated *local gravity force field* which eliminates Earth gravity's weight and inertial effects . A pilot aboard the craft using abundant power from a portable antimatter reactor on board can direct that secondary gravitational force-field so as to lift the craft from the ground, and then switch to powering the craft forward, or backward, by manipulating the polarity of the kinemassic-field body's antigravity field to activate either its inherent attraction to, or repellency from, Earth's gravitational field, depending on the polarities of their respective gravity fields.

Once in space beyond Earth's gravity field, the pilot can then switch the secondary-gravity ['antigravity'] kinemassic field to target the destination in space (e.g., the Moon), and activate the attraction-force option. Since the craft is now weightless and there is no air resistance, it zips rapidly towards its target.

- Important information about the engineering of this third Strong Force Field technology* is available in Bob Lazar's courageous expose' video, 'Bob Lazar: Area 51 and Flying Saucers" (on YouTube.com or on Netflix.com .)

*Lest anyone think this **Generating a Secondary Artificial Gravitational Force Field** is a flight of someone's imagination, the U.S. Patent Office has granted a patent for that technology, (**U.S. Patent 3,626,605**), "Method and Apparatus for Generating a *Secondary* Gravitational Force Field". The Patent was issued to GE scientist Henry William Wallace in 1971. That Patent is worth reading because it explains the process of generating an artificial gravity field, how to produce gravity shielding, and how to neutralize the hold of Earth's gravity to create weightlessness. The Patent does not say so, but

Dr. Boylan has received indication that this technology was discovered by GE scientists who back-engineered the power plant of the UFO which was shot down, crashed, and was retrieved by Army Air Forces teams north of Roswell, New Mexico in 1947.

Army Pentagon Colonel Phillip Corso was given the assignment of quietly distributing various parts of crashed UFOs to select technology companies like General Electric who promised not to reveal the extraterrestrial origin of the advanced technology.

For useful context, let us consider Antigravity Technology's Time-Line .
1947 Two UFOs crash near Roswell, New Mexico and are retrieved by Army Air Forces teams.

1961 Army Colonel Phillip Corso was given the assignment of distributing various parts from the Roswell flying disc to top U.S. technology industries and military research labs to advance American technological sophistication and understanding.

1985 Nuclear physicist Bob Lazar joined other scientists such as physicist Dr. Michael Wolf working at the S-4 Annex (Papoose Lake National Laboratory), and Area 51 (Groom Lake National Laboratory), where they analyze the Roswell and other UFOs' levitation and propulsion systems.

One night in 1992 Bob Lazar and other UFO enthusiasts, (including Dr. Boylan) staked out positions next to Nevada Highway 375 at night and watched successful test flights of U.S. antigravity craft above the Groom Mountains ridgeline between HWY 375 and Area 51, Nevada. (What they saw that night were the 'Great Pumpkin' version of brightly-shining Antigravity Discs, manufactured by Northrop-Grumman Aerospace Corporation's black projects division.)

Some After-thoughts by Dr. Boylan

Dr. Boylan has published his findings at national and international conferences, in specialty journals, and in media interviews. This in turn brought him to the attention of officials currently or formerly in highly-

classified sectors of the government, military, and intelligence agencies. These individuals decided to leak certain additional information through him, knowing Dr. Boylan would thus serve as a conduit to bring such leaked information to the attention of the portion of the public interested and ready for such information.

Dr. Boylan made it a top research task, starting in 1992, to reconnoiter, observe, and in many instances penetrate many of the most important UFO-related government installations. He figured that the knowledge gained could be very helpful to the experiencers who consult with him, to help them feel secure that they had not hallucinated when they saw Star Visitors, and that such advanced technology exists, and in fact, the American government has some of this technology. Additionally, hundreds of experiencers of close encounters shared with him information they possessed from their encounters, including about U.S. antigravity craft, either by reason of being told such things by the Star Visitors, or by being kidnapped by Cabal paramilitary mercenaries and taken aboard one of *their* crafts. This added to his fund of information on U.S. advanced antigravity craft.

While Dr. Boylan has gathered, or been entrusted by others with, considerable information on secret American aerospace craft, he does not purport to know everything that is in the U.S. classified aerospace inventory, nor everything about the operations and capabilities of the crafts that he has identified. What he does know is presented here. He has held nothing back.

America has used its enormous wealth to become the global super-power. The world awaits the day when America finds its soul, and pays more attention to matters of spirit, mind, and metaphysical and moral development, and withdraws from its over-addiction to highly advanced technology.

It has been said that if the American people knew what the military had in their arsenal today, they wouldn't believe it, and would think that someone was fantasizing about a new George Lucas *Star Wars* movie. But it's not science-fiction. The future is already here!

The *implications of these advanced antigravity craft*, back-engineered by Humans from ET examples, are several.

The United States and a select very few Allies operate a variety of reduced-gravity and fully-antigravity craft.

But some antigravity technology is also possessed by Communist China and autocratic Russia, both ruled by autocrats. Both in turn are shadow-manipulated by a global-control cartel known informally as 'the Cabal'.

The Cabal are a cartel of super-powerful oligarchs and their minions aiming at global dominance. The Cabal are the ones primarily demanding that the UFO Cover-Up continue. The Cabal are being slowly discovered and losing power. **Their 'Final Solution' is to use their neo-Soviet and ChiCom antigravity crafts to conduct an 'Alien Invasion' UFO Fleet Space War on selected global cities, blamed on the ultimate Foreign Invader ['ETs'], and use the resulting chaos to take complete control of the world via Global Martial Law.**

What can we do about this as Star Seed adults/Star Kids and other humans of good will?

1) First, keep ourselves informed about dangerous and evil uses to which antigravity (and other quantum) technology can be applied. 2) Contact our political representatives to oppose policies and weapons systems development oriented towards offensive attacks from space.

3) Encourage the declassification and release of antigravity advanced technology into the civilian sector , where *its peaceful*

use can revolutionize transportation, hydro-wind-ZPE energy generation, food production, home-building projects, etc., and stop the advance of petrochemical-caused Climate Change. 4) Beware

False Flags. The existence of this advanced technology is a two-edged sword for the Cabal. Not only is the existence of antigravity technology starting to get out to the public, but so also is the very existence of a massive worldwide organization conducting the UFO Cover-Up and conducting unauthorized confiscation of Star Visitor technology. As the public becomes aware that the Cabal have unfairly obtained this technology for over 75 years, the public will become outraged at the Cabal for their greed and selfishness. This then becomes **the opportunity to expose and discredit and eliminate the Cabal, Number One Obstacle to human safety and progress.**

How the Star Visitors Accomplish Spaceflight and Celestial Navigation

This **Second Addendum** by Wendi Powers, Dr. Boylan's close associate, passing on information from the Zeta Star Visitors. [Wendi's address is BlackfootTurtle@aol.com]

Wendi says: 1) Zeta craft skin is very unique. Zeta crafts are self healing - as long as they are not too messed up, small things repair automatically. The skin of Zeta craft is amazing. It is actually nano-technology, and the small cells (*not actually cells, but they are alive and thoughtful individual quark units which make up the material in a uniform state) - these cells communicate internally and share the common service of keeping the whole craft healthy. They watch out over each other and if one unit is hurt, they will heal the injured one. In [a Science Channel show, Future Cars*], it showed how a car can get a scratch and the paint is a type of intelligent polymer that will self-heal the scratch. * <http://science.discovery.com/tv-schedules/series.html?paid=48.15363.25316.33193.1>

Wendi says, 'I have actually held a piece of Zeta craft from the Roswell crash and talked with the square piece. It responded directly to my touch and requests.'

2) Cars of the future will be linked with the driver. For a Zeta craft, this is the same thing on an advanced level. The Zeta craft listens to the heart energy of the one in communication with it. It will not respond to energy of ego. This is also why the [monstrously-egotistic] Cabal who have captured Zeta craft can not figure out how to drive them. One time I was called in [by her Cabal captors when she was a kidnapped young person] to try to make a Zeta craft fly - along with some other people. It was very easy for me to have the craft respond and get off the ground because of how the craft responds to the pilot. Of course after I figured out the [Cabal] person was trying to find out how I was able to make the Zeta craft get off the ground in the hanger, I immediately knew to shut it down. I told them I had no idea how I did it. Just like the cars in our own future, if the car/craft senses that the one driving is not supposed to be

doing so - they just won't work.

3) Cars of the future will be interconnected through what the [movie] is calling 'the Matrix'. They will be on a grid form of travel. They hope this will keep cars from crashing. (My father actually designed a car system back in 1940's that did exactly this based on magnetic engineering - but anyway...) Zeta craft naturally do this. In fact, all the Star Nations craft I ever heard about among the many Species do this already. The Space Beacon System ["Monoliths"] is the brain behind what goes on in the [space] energy grids. The Space Beacon keeps all the information of where craft are and such so they don't smash into each other all the time. Of course that system is based on not just our simple energy level but on many millions of energy systems that all interlap and overlap. It is actually a very amazing thing to see in person because the technology the Star Folks use to do this is so cool. In 1978 when I was 8 and got to go to the City of Light [deep in space], the two Star Folks who took me had an on-board system that was holographic. And they were asking the computer or Star-Ship system, along with talking to each other (one male and one female), about the best path to take back to their home where they wanted to take me. They were pointing out something that they were trying to avoid and talking about how to go around that. (I say talking but it was telepathic speech not human words, but I could understand the energy of what they were saying). But after they settled on the path they wanted to take, their Star Ship took over. And I knew it was automatic and would not hit anything. And from the Zeta craft I have seen the same type of thing - but a little different.

4) Cars of the future here on Earth are being shown [on the Science Channel program] to be autonomous. But we need to consider this a little more in our development choices. The Zeta craft actually feed back to the Zeta pilot whatever the pilot wants at the time. If it is on auto-mode going somewhere specific, and the Zeta decide they want to swing by Earth to make a visit over [e.g., Washington, DC], well, it is a simple single thought to do so. And the Zeta craft can go from automatic functioning to completely in the hands of the pilot. I find this very amazing actually because of the life that the Zeta craft has. When the one was shot down in Roswell, it was fully under control of Zeta pilot

rather than self-mode. Self-mode would have protected the craft totally, and it would have left. But the Zetas aboard made a choice. In that situation, the Zeta pilot made a choice based on the heart energy of their group. I still do not understand that entire situation, but I do know, based on asking Zeta, that a Human [on the ground] would have been killed had they not make the choice they made. And Zeta work very hard to cause no harm. It was a split-second decision when either answer was not ideal. But the point is that the choice of action is finally in the hands of the [Zeta] pilot.

Spacetime Metric

In subject area: [Physics and Astronomy](#)

A spacetime metric in Physics and Astronomy refers to the signature chosen for the metric tensor, such as $(+, -, -, -)$, which describes the geometry of spacetime in terms of distances and intervals between events.

Stationary ring solitons in field theory — Knots and vortons

Eugen Radu, Mikhail S. Volkov

Abstract

We review the current status of the problem of constructing classical field theory solutions describing stationary [vortex rings](#) in [Minkowski space](#) in 3+1 dimensions. We describe the known up to date solutions of this type, such as the static knot [solitons](#) stabilized by the topological Hopf charge, the attempts to gauge them, the anomalous solitons stabilized by the Chern–Simons number, as well as the non-Abelian monopole and sphaleron rings. Passing to the rotating solutions, we first discuss the conditions ensuring that they do not radiate, and then describe the spinning Q-balls, their twisted and gauged generalizations reported here for the first time, spinning skyrmions, and rotating monopole–antimonopole pairs. We then present the first explicit construction of global vortons as solutions of the elliptic [boundary value problem](#), which demonstrates their non-radiating character. Finally, we describe the analogs of vortons in the Bose–Einstein condensates, analogs of spinning Q-balls in the non-linear optics, and also moving vortex rings in [superfluid helium](#) and in ferromagnetics.

Introduction

Stationary vortex loops are often discussed in the literature in various contexts ranging from the models of condensed matter physics [11], [12], [17], [41], [124], [137], [146], [147], [149], to high energy physics and cosmology [29], [45], [46], [48], [165], [177]. Such objects could be quite interesting physically and might be responsible for a plenty of important physical phenomena, starting from the structure of quantum superfluids [54] and Bose–Einstein condensed alkali gases [117] to the baryon asymmetry of the Universe, dark matter, and the galaxy formation [165]. These intriguing physical aspects of vortex loops occupy therefore most of the discussions in the literature, while much less attention is usually paid to their mathematical existence. In most considerations the existence of such loops is discussed only qualitatively, using plausibility arguments, and the problem of constructing the corresponding field theory solutions is rarely addressed, such that almost no solutions of this type are explicitly known.

The physical arguments usually invoked to justify the loop existence arise within the effective macroscopic description of vortices [1], [129]. Viewed from large distances, their internal structure can be neglected and the vortices can be effectively described as elastic thin ropes or, if they carry currents, as thin wires [32], [33], [34], [35], [122]. This

suggests the following engineering procedure: to ‘cut out’ a finite piece of the vortex, then ‘twist’ it several times and finally ‘glue’ its ends. The resulting loop will be stabilized against contraction by the potential energy of the twist deformation, that is by the positive pressure contributed by the current and stresses [43], [42], [86], [130]. Equally, instead of twisting the rope, one can first ‘make’ a loop and then ‘spin it up’ thus giving to it an angular momentum to stabilize it against shrinking [47], [48]. Depending on whether they are spinning or not, such loops are often called in the literature vortons and knots (also springs), respectively.

These macroscopic arguments are suggestive. However, they cannot guarantee the existence of loops as stationary field theory objects, since they do not take into account all the field degrees of freedom that could be essential. Speaking more rigorously, one can prepare twisted or spinning loop configurations as the initial data for the fields. However, nothing guarantees that these data will evolve to non-trivial equilibrium field theory objects, since, up to few exceptions, the typical field theory models under consideration do not have a topological energy bound for static loop solitons. For spinning loops the situation can be better, since the angular momentum can provide an additional stabilization of the system. However, nothing excludes the possibility of radiative energy leakages from spinning loops. Since there is typically a current circulating along them, which means an accelerated motion of charges, it seems plausible that spinning loops should radiate, in which case they would not be *stationary* but at best only quasistationary. In fact, loop formation is generically observed in dynamical vortex network simulations (although for currentless vortices), and these loops indeed radiate rapidly away all their energy (see e.g. [26]).

The lack of explicit solutions renders the situation even more controversial. In fact, although there are explicit examples of loop solitons in *global* field theory, which means containing only scalar fields with global internal symmetries, almost nothing is known about such solutions in *gauge* field theory. Vortons, for example, were initially proposed more than 20 years ago in the context of the local $U(1) \times U(1)$ theory of superconducting cosmic strings of Witten [177]. However, not a single field theory solution of this type has been obtained up to now. Search for static knot solitons in the Ginzburg–Landau-type gauge field theory models has already 30 years of history, the result being always negative. All this casts some doubts on the existence of stationary, non-radiating vortex loops in physically interesting gauge field theory models. However, rigorous no-go arguments are not known either. As a result, the existence of such solutions has been neither confirmed nor disproved.

Interestingly, *exact* solutions describing ring-type objects are known in curved space. These are black rings in the multidimensional generalizations of General Relativity — spinning toroidal black holes (see [58] for a review). It seems therefore that Einstein’s field equations, notoriously known for their complexity, are easier to solve than the non-linear equations describing loops made of interacting gauge and scalar fields in Minkowski space.

It should be emphasized that the problem here is not related to the dynamical stability of these loops. In order to be stable or unstable they should first of all exist as stationary field theory solutions. The problem is related to the very existence of such solutions. One should be able to decide whether they exist or not, which is a matter of principle, and

this is the main issue that we address in this paper. Therefore, when talking about loops stabilized by some forces, we shall mean the force balance that makes possible their existence, and not the stability of these loops with respect to all dynamical perturbations. If they exist, their dynamical stability should be analyzed separately, but we shall call *solitons* all localized, globally regular, finite energy field theory solutions, irrespectively of their stability properties. It should also be stressed that we insist on the *stationarity* condition for the solitons, which implies the absence of radiation. Quasistationary loops which radiate slowly and live long enough could also be physically interesting, but we are only interested in loops which could live infinitely longtime, at least in classical theory.

Trying to clarify the situation, we review in what follows the known field theory solutions in Minkowski space in $3+1$ dimensions describing stationary ring objects. We shall divide them in two groups, depending on whether they do have or do not have an angular momentum. Solutions without angular momentum are typically static, that is they do not depend on time and also do not typically have an electric field. We start by describing the static knot solitons stabilized by the Hopf charge in a global field theory model. Then we review the attempts to generalize these solutions within gauge field theory, with the conclusion that some additional constraints on the gauge field are necessary, since fixing only the Hopf charge does not seem to be sufficient to stabilize the system in this case. We then consider two known examples of static ring solitons in gauge field theory: the anomalous solitons stabilized by the Chern–Simons number, and the non-Abelian monopole and sphaleron rings.

Passing to the rotating solutions, we first of all discuss the issue of how the presence of an angular momentum, associated to some internal motions in the system, can be reconciled with the absence of radiation which is normally generated by these motions. One possibility for this is to consider time-independent solitons in theories with local internal symmetries. They will not radiate, but it can be shown for a number of important field theory models that the angular momentum vanishes in this case. Another possibility arises in systems with global symmetries, where one can consider *non-manifestly* stationary and axisymmetric fields containing spinning phases. Such fields could have a non-zero angular momentum, but the absence of radiation is not automatically guaranteed in this case. The general conclusion is that the existence of non-radiating spinning solitons, although not impossible, seems to be rather restricted. Such solutions seem to exist only in some quite special field theory models, while generic spinning field systems should radiate.

Nevertheless, non-radiating spinning solitons in Minkowski space in $3+1$ dimensions exist, and we review below all known examples: these are the spinning Q-balls, their twisted and gauged generalizations, spinning Skyrmions and rotating monopole–antimonopole pairs. In addition, there are also vortons, and below we present for the first time numerical solutions of elliptic equations describing vortons in the global field theory limit. Although global vortons have been studied before by different methods, our construction shows that they indeed exist as stationary, non-radiating field theory objects.

We also discuss stationary ring solitons in non-relativistic physics. Surprisingly, it turns out that the relativistic vortons can be mapped to the ‘skyrmion’ solutions of the Gross–

Pitaevskii equation in the theory of Bose–Einstein condensation. In addition, it turns out that Q-balls can describe light pulses in media with non-linear refraction — ‘light bullets’. Finally, for the sake of completeness, we discuss also the moving vortex rings stabilized by the Magnus force in continuous media theories, such as in the superfluid helium and in ferromagnetics.

In our numerical calculations we use an elliptic PDE solver with which we have managed to reproduce most of the solutions we describe, as well as obtain a number of new results presented below for the first time. The latter include the explicit vorton solutions, spinning twisted Q-balls, spinning gauged Q-balls, as well as the ‘Saturn’, ‘hoop’ and bi-ring solutions for the interacting Q-balls. We put the main emphasis on describing how the solutions are constructed and not to their physical applications, so that our approach is just the opposite and therefore complementary to the one generally adopted in the existing literature. As a result, we outline the current status of the ring soliton existence problem — within the numerical approach. Giving mathematically rigorous existence proofs is an issue that should be analyzed separately. It seems that our global vorton solutions could be generalized in the context of gauge field theory. The natural problem to attack would then be to obtain vortons in the electroweak sector of Standard Model.

In this text the signature of the Minkowski spacetime metric $g_{\mu\nu}$ is chosen to be $(+, -, -, -)$, the spacetime coordinates are denoted by $x_\mu = (x_0, x_k) \equiv (t, x)$ with $k=1,2,3$. All physical quantities discussed below, including fields, coordinates, coupling constants and conserved quantities are dimensionless.

Knot solitons

Let us first consider solutions with zero angular momentum stabilized by their intrinsic deformations. We shall start by discussing the famous example of static knotted solitons in a non-linear sigma model. Since this is the best known and also in some sense canonical example of knot solitons, we shall describe it in some detail. We shall then review the status of gauge field theory generalizations of these solutions.

Knot solitons in gauge field theory

As we have seen, fixing only the topological charge does not guarantee the existence of knot solitons in gauge field theory. In order to obtain such solutions one needs to constraint the gauge field in order that it could not be deformed to zero. Below we describe two known examples of such solutions.

Angular momentum and radiation in field systems

We are now passing to the spinning systems with the ultimate intention to discuss spinning vortex loops stabilized by the centrifugal force — vortons. As was already said in the Introduction, usually vortons are considered within a qualitative macroscopic description as loops made of vortices and stabilized by rotation. This description is suggestive, but it does not take into account the radiation damping. At the same time, the presence of the vorton angular momentum requires some internal

Explicit examples of stationary spinning solitons

Before coming to vortons, one can wonder, in view of the above discussion, if there exist at all any known examples of non-radiating spinning solitons. As we said, for the $SU(2)$ magnetic monopoles, dyons and sphalerons there are no spinning generalizations, at least in the manifestly stationary and manifestly axisymmetric case. Nevertheless, explicit examples of spinning solitons in Minkowski space in $3+1$ dimensions exist and below we shall review all known solutions of this type. These are the

Vortons

We are now ready to explicitly construct vortons as localized, finite energy solutions of the elliptic field equations. By construction, they are stationary and non-radiating. Our results can be viewed as complementary to those obtained by Battye, Cooper and Sutcliffe [17] (although in a completely different context) and by Lemperier and Shellard [118].

Ring solitons in non-relativistic systems

So far we have been considering relativistic ring solitons that could be relevant in models of high energy physics. At the same time, similar objects also exist in non-relativistic physics, and below we shall consider some of them which are most closely related to our previous discussion.

A famous example of soliton-type toroidal systems is provided by the magnetically confined plasma in the TOKAMAK's. However, since considering this subject would lead us far beyond the scope of our present

Concluding remarks

We have reviewed the known field theory solutions describing stationary vortex loops. From the physical point of view, loops of magnetic flux would perhaps be the most interesting. However, as we have seen, almost all explicit solutions describe vortex loops in global field theories, which are effective theories with a relatively limited range of applicability. Perspectives for generalizing these solutions in the context of gauge field theory do not look very promising at the moment, at least

QUANTUM GRAVITY

Carlo Rovelli

THE NATURE OF SPACE AND TIME

GR has modified the way we understand space and time. Combining GR with QM requires a further modification of these notions. It is important, however, to clearly distinguish the modifications of the notions of space and time required by QG from the ones already implied by GR alone. These are briefly summarized in Section 4.1 below. Section 4.2 and 4.3 then discuss the notions of space and time in QG.

4.1 The physical meaning of GR

GR is the discovery that spacetime and the gravitational field are the same entity. What we call “spacetime” is itself a physical object, in many respects similar to the electromagnetic field. We can say that GR is the discovery that there is no spacetime at all. What Newton called “space”, and Minkowski called “spacetime”, is nothing but a dynamical object — the gravitational field — in a regime in which we neglect its dynamics.

In newtonian and special relativistic physics, if we take away the dynamical entities — particles and fields — what remains is space and time. In general relativistic physics, if we take away the dynamical entities, nothing remains. The space and time of Newton and Minkowski are reinterpreted as a configuration of one of the fields, the gravitational field. This implies that physical entities — particles and fields — are not all immersed in space, and moving in time. They do not live on spacetime. They live, so to speak, on one another.

In classical GR it is customary to maintain the expressions “space” and “time” to indicate aspects of the gravitational field. But in the quantum theory, where the field can have quantized “granular” properties and its dynamics is quantized and therefore only probabilistic, most of the “spatial” and “temporal” features of the gravitational field are probably lost.

This absence of the familiar spacetime “stage” is called the *background independence* of the classical theory. Technically, background independence is realized by the gauge invariance of the GR action under (active) diffeomorphism. A diffeomorphism is a transformation that smoothly drags all dynamical fields and particles on the four-dimensional coordinate manifold. In turn, gauge invariance under diffeomorphism (or *diffeomorphism invariance*) is the consequence of the combination of two properties of the action: its invariance under arbitrary changes of coordinates (or *general covariance*) and the fact that there is no non-dynamical “background” field. Thus: *background independence* = *diffeomorphism invariance* = (*general covariance* + absence of non-dynamical background fields). These notions are illustrated in more detail below.

Diffeomorphism invariance

Pre-general-relativistic field theories are formulated in terms of a spacetime manifold M , and a set of fields $\phi_1, \dots, \phi_n$ on M . The manifold M is a (pseudo-)metric space whose points $P \in M$ represent the physical points of spacetime. Spacetime points are labelled by coordinates $x = (x^1, x^2, x^3, x^0)$ that represent the reading of measuring devices: clocks and distance-measuring devices (“rods”). More precisely, M is equipped

with a (pseudo-)distance function $d(x, y)$ interpreted as the 4-interval between the two points x and y : a negative $d^2(x, y)$ gives the time measured by a clock in inertial motion between x and y ; a positive $d^2(x, y)$ gives the proper length of a rod with the ends on x and y , in a state of inertial motion with respect to which x and y are simultaneous according to Einstein's definition of simultaneity; a null $d(x, y)$ indicates that light travels in vacuum from x to y . Notice that pre-general-relativistic physics deals with (relations between) two distinct types of measurements: (i) spacetime measurements measuring spacetime observables, performed by means of clocks and distance-measuring devices, and (ii) field measurements, measuring field observables, namely the values (or functions) of the fields $\phi_1, \dots, \phi_n$.

This same interpretation framework is used in special-relativistic QFT. The only difference is that field observables can be quantized. The number of excited quanta has a particle interpretation. In a typical high energy scattering experiment, for instance, the field observable (ii) is the number of particles revealed by a particle detector (which is a field measuring device); while the spacetime observable (i) is the momentum of the particle, determined by measuring the spacetime position of the detector.

The theory does not predict the value of field observables ϕ alone, or spacetime observables x alone, but only combinations of the two, such as the value $\phi(x)$ of a field ϕ at a certain spacetime location x . Spacetime and field observables are both quantities that have a direct operational interpretation; they can be called “partial observables”. On the other hand, the quantities that can be predicted by the theory, such as $\phi(x)$, for a given position x , can be called “complete observables”.

The interpretation of a *general* relativistic field theory is different. In such a theory there is a field g representing the gravitational field and possibly other fields, representing other dynamical variables. These fields are defined on a differentiable manifold M , coordinatized by coordinates x . The formal structure of a general relativistic field theory is therefore similar to the structure of a pre-general-relativistic field theory. But two major differences force a different interpretation. First, the manifold M on which the fields are defined is not a metric manifold. The gravitational field g equips M with a metric structure $d_g(x, y)$.¹ Therefore clocks and distance-measuring-devices measure properties of the gravitational field g . It follows that the distinction between spacetime observables of the kind (i) and field observables of the kind (ii) is blurred. This blurring of the distinction between the two kind of partial observables is a crucial conceptual novelty of GR.

Second, the field equations are invariant under a transformation of the fields called active diffeomorphisms. An active diffeomorphism $g \rightarrow \tilde{g}$ is determined by (but should not be confused with) a smooth invertible function $f: M \rightarrow M$. Under a diffeomorphism transformation, the field g and all other fields are “dragged along” M by f . For instance, the transformed field $\tilde{g}$ defines a new distance function $d_{\tilde{g}}(x, y)$ which is related to the one defined by g by

$$(10) d_{\tilde{g}}(f(x), f(y)) = d_g(x, y).$$

In words: the distance between the two points $f(x)$ and $f(y)$, defined by the field $\tilde{g}$ is the same as the distance between the two points x and y defined by g .

The importance of this invariance of the field equations is due to the following. An active diffeomorphism may modify a solution of the GR equations in the future of a certain time surface t_0 , without modifying it at all in the past of t_0 . Therefore two distinct solutions of the [equations of motion](#) can be equal in the past and differ in the future.

This fact gives us a choice: either (i) we interpret the theory as an indeterministic theory, where the future is not determined by the past. Or (ii) we interpret active diffeomorphisms as a “gauge invariance”: that is, we postulate that the complete observables of the theory are only given by quantities that are invariant under this transformation. The alternative (i) is not viable, because experience shows that classical [gravitational physics](#) is completely deterministic. We are therefore forced to alternative (ii), which has heavy interpretative consequences.

To understand these consequences, let P be a point of M . Let $\varphi(P)$ be any property of the fields at P . For instance, $\varphi(P)$ may represent a value of the [electromagnetic](#) field at P or the spacetime scalar curvature at P , or something similar. None of these properties is invariant under active diffeomorphism. Therefore, it follows from the argument above that none of these properties can be predicted by the theory. Therefore the theory does not determine the physics at spacetime points $P \in M$.

At first this conclusion might sound bewildering: if physics does not predict what happens at spacetime points, what can it predict? In fact, historically, Einstein himself got at first confused and frustrated by this observation, to the point of stepping back from the diffeomorphism invariance he previously expected GR to have [Norton, 1984]. Einstein's version of the argument given above is called the “hole argument” (because Einstein considered a diffeomorphism affecting only a finite region of spacetime, empty of matter, or a “hole”), and was presented in [Einstein and Grossmann, 1914]. On this argument, and the discussion it has raised, see for instance [Earman, 1987; Earman, 1989; Belot, 1998; Earman, 2001; Pauri and Vallisneri, 2002] and references therein. Later however, Einstein changed his mind and accepted both diffeomorphism invariance and the conclusion (ii), realizing that this conclusion fully implemented his intuition on the very central physical meaning of the general relativistic conceptual revolution.

The way out of the puzzle is to understand that in the general-relativistic context the points of the manifold do not represent physical entities with an existence independent from the fields. Asking what are the properties of the fields at P is meaningless. Spacetime locations can only be determined by the fields themselves, or, by any other dynamical object we are considering. For instance, if the theory we consider includes two particles and the trajectories of the two particles happen to meet once, then the meeting of the particles determines a spacetime point. The theory is able to predict the value of the fields and any other physical properties at the spacetime point determined by the meeting of the particles. However, this point cannot be naively identified as a point of M , because the same physical situation can be represented by the set of dynamical variables obtained by an active diffeomorphism, where the particles meet now at a different point, say Q of M . The value of the fields at the point where the particles meet is invariant under such a transformation, because the particles' trajectories and the fields are dragged along M together. Einstein called this way of determining location in terms of the dynamical objects (fields and particles) of the theory itself, “spacetime coincidences”.

Thus, a general relativistic theory does not deal with values of dynamical quantities at given spacetime points: it deals with values of dynamical quantities at “where”s and “when”s determined by other dynamical quantities.

Strictly speaking also in the pre-general-relativistic context physics deals with values of dynamical quantities at “where”s and “when”s determined by other physical quantities,

because the times and distances used to determine location are physical quantities. But in the pre-general-relativistic context we can make a strict separation between: (i) “spacetime”, viewed as a background entity, and measured by clocks and rods that one considered non-dynamical, and (ii) dynamical variables. In the general-relativistic context, on the other hand, this separation is lost, time and distance measurements are reinterpreted as measurements of the gravitational field, on the same footing as other field measurements, and there is no distinction between non-dynamical background and dynamical physical variables.

Physical meaning of the coordinates

A consequence of the above is that in the general-relativistic context the physical interpretation of the coordinates x is different from their interpretation in the non-general-relativistic context. In the general-relativistic context the coordinates x have no interpretation at all: observable quantities in GR correspond to quantities of the theory that are independent of the coordinates x . Recall that the non-general-relativistic coordinates represent the reading of clocks and rods: in the general-relativistic context, the reading of clocks and rods is represented by the non-local function $d_g(x, y)$ of the gravitational field. The fact that the non-general-relativistic coordinates x and the general-relativistic coordinates x are denoted in the same manner is only an unfortunate historical accident.

To illustrate in which sense observable quantities are independent of the coordinates x , consider a typical general-relativistic measurement. A standard application of GR is in precision measurements and precision modeling of solar system dynamics. In this context, partial observable quantities are the “instantaneous” distances d_p between the Earth and the different planets, defined as the proper time elapsed on Earth (measured by a clock at rest on Earth) while a radar signal goes from Earth to a planet p and back. Fixing an arbitrary initial event on Earth, one additional partial observable can be obtained as the proper time τ from this event along the Earth trajectory. Complete observables are then the values $d_p(\tau)$ of the planet distances, at different local proper times τ . A general relativistic model of the solar system, with appropriately chosen initial data, can predict $d_p(\tau)$ for all p 's and all τ 's, and these predictions can be compared with experience. In building up this model, we choose an arbitrary coordinatization x of the solar system region, and express the gravitational field, the electromagnetic field, and the planets' positions in this coordinate system. The predicted quantities $d_p(\tau)$ are complicated non-local functions of the fields and planets' positions, which are independent of the coordinates x chosen. To be sure, the observable τ is introduced here only for convenience. We can equivalently express the predictions of the theory simply as a set of relations $f(d_p) = 0$ that must hold between the partial observables d_p .

General covariance and Kretschmann objection

The invariance of GR under active diffeomorphisms follows from two properties of the GR field equations. First, they are generally covariant. That is, they maintain the same form under any smooth change of coordinates $x \rightarrow x'(x)$ on M . This means that there is no coordinate systems on M which is preferred a priori. Second, there are no fixed non-dynamical fields in the field equations.

The first property, namely general covariance, is the property that Einstein most insisted upon, and that guided him in finding GR. The requirement of general

covariance still plays a major role in selecting physical theories compatible with what we have understood about the world as a result of the general relativistic revolution.

However, general covariance *alone* is not excessively significative. Indeed, any field equation can be written in an arbitrary coordinate system. This fact was pointed out by Kretschmann shortly after Einstein wrote GR [Kretschmann, 1917], and has raised much discussion. As an example, consider the field equation

$$(11) (\partial T^2 - \partial X^2 - \partial Y^2 - \partial Z^2) \phi(X, Y, Z, T) = 0.$$

If we introduce arbitrary coordinates x (with components x^μ) as functions $x^\mu = x^\mu(X, Y, Z, T)$ (with inverse $X(x), Y(x), Z(x), T(x)$), the wave equation 11 becomes the generally covariant equation

$$(12) \square_g \phi(x) \equiv \partial_\mu \det g(x) g^{\mu\nu}(x) \partial_\nu \phi(x) = 0,$$

In this equation, the unknown is $\phi(x)$, while $g^{\mu\nu}(x)$ and $\det g(x)$ are the inverse and the determinant of the *fixed* field

$$(13) g_{\mu\nu}(x) = \partial X(x) \partial x_\mu \partial X(x) \partial x_\nu + \partial Y(x) \partial x_\mu \partial Y(x) \partial x_\nu + \partial Z(x) \partial x_\mu \partial Z(x) \partial x_\nu - \partial T(x) \partial x_\mu \partial T(x) \partial x_\nu.$$

The field theory for the scalar field ϕ defined by equation 12 is *not* diffeomorphism invariant, because in distinct coordinate systems the field equations for the unknown ϕ are different, in the sense that they are determined by different functions $g_{\mu\nu}(x)$.

Equation 12, on the other hand, can become one of the equations of a diffeomorphism invariant theory in which $g_{\mu\nu}(x)$ is also one of the unknown, namely a dynamical field. Therefore whether or not a theory is diffeomorphism invariant is not determined just by the aspect of an equation, but by the full specification of the dynamical quantities and their equations of motion.

Einstein's insistence on general covariance alone, however, should probably not be interpreted as a lack of clarity on his part, but only as his effort to emphasize the importance of a step that was *necessary*, not sufficient, to write a successful relativistic field theory.

In addition, like all formal properties of physical theories, even full diffeomorphism invariance, should probably not be interpreted as a rigid selection principle, capable of selecting physical theories *just by itself*. With sufficient acrobatics, any theory can perhaps be re-expressed in a diffeomorphism invariant language. The same is true for any other formal invariance property. For instance, any theory can be rewritten as a rotational invariant theory, or with any other desired invariance property, by simply adding variables.

As an example, equation 11 can be viewed as physically equivalent to the diffeomorphism invariant system

$$(14) \square_g \phi(x) = 0, \text{ Riem}[g] = 0,$$

where $\text{Riem}[g]$ is Riemann's curvature and the unknowns are now the two fields ϕ and g . But there are prices to pay. First, this theory has a “fake” dynamical field, since g is constrained to a single solution up to gauges, by the second equation of the system. Having no physical degrees of freedom, g is physically a fixed background field, in spite of the trick of declaring it a variable and then constraining the variable to a single solution. Second, we can insist on a lagrangian formulation of the theory (14) [Sorkin, 2002], but to do this we must introduce an additional field, and it

can then be argued that the resulting theory, having an additional field is different from (12) [Earman, 1989].

Diffeomorphism invariance is the key property of the mathematical language used to express the key conceptual shift introduced with GR: the world is not formed by a fixed non-dynamical spacetime structure, which defines localization and on which the dynamical fields live. Rather, it is formed solely by dynamical fields in interactions with one another. Localization is only defined, relationally, with respect to the fields themselves.

Relationalism and substantivalism

A non-dynamical background space was used by Newton. The first part of the *Principia*, Newton argues very explicitly that we must assume the existence of space as an entity. This part can be read as a polemic against the long dominant, and in particular Descartes's, relational understanding of space.

The two traditional views about space, absolute ("space is an entity") and relational ("space is a relation between entities"), suitably modified to take into account scientific progress, continue in contemporary philosophy of science under the names of *substantivalism* and *relationalism*.

We can say that Einstein has "unmasked" the entity introduced by Newton (which much disturbed Leibniz): Newton's space is nothing else than a field like the others, though Newton considered it in a regime in which its dynamics could be neglected. Localization in space and in time, introduced by Newton against Descartes's relational localization, is revealed by Einstein to be, after all, still a relational location — in the sense of Descartes —, with respect to a specially chosen entity: the gravitational field. In a sense, we can therefore say that GR realizes a full return to a relational definition of space and time, after the Newtonian substantivalist parenthesis.

In other words, in prerelativistic physics, spacetime is a sort of structured container which is the home of the world. In general-relativistic physics, on the other hand, there is nothing of the sort. There are only interacting fields (including the gravitational field) and particles: the only notion of localization which is present in the theory is relative: dynamical objects (fields and particles) are localized only with respect to one another. This is the notion of relational space defended by Aristotle and Descartes, against which Newton wrote the initial part of the *Principia*. Newton had two points in his favor: the physical reality of inertial effects such as the concavity of the water in the bucket of his famous bucket experiment, and the immense empirical success of his theory based on absolute space. Einstein has provided an alternative interpretation for the cause of the concavity — the interaction with an entity: the local gravitational field — and a theory based on relational space that is empirically far more effective than [Newton theory](#). Einstein has therefore reopened the possibility of a relational understanding of space and time, which was closed by Newton's bucket.

At the basis of Cartesian relationalism was the notion of "contiguity". Two objects are contiguous if they are adjacent to one another. Space is the order of things with respect to such contiguity relation. At the basis of the spacetime structure of GR there is a very similar notion: Einstein's "spacetime coincidence" is strictly analogous to Descartes' "contiguity".

The key to this novel relational understanding of space and time is Faraday's revolutionary idea that a field is a physical entity. Recall that Faraday visualized a field as a family of real lines filling up everything. Einstein's entire theoretical work fully

implements this realistic interpretation of the fields. In Einstein popularscience writing, the gravitational field is a huge “jelly fish”, a better metaphor than the lines of Faraday. Entities are not just particles, but also fields, the gravitational field is one field among the others. These entities are localized only with respect to one another.

A substantivalist position can nevertheless still be –and in fact is still– defended. Einstein's discovery that Newtonian spacetime and the gravitational field, are the same entity, can also be expressed by saying that there is no gravitational field: it is spacetime that has dynamical properties. This choice is not uncommon in the literature. The difference with the language used here is only a matter of choice of words. The substantivalist can therefore claim use the that, according to GR, “spacetime is an entity”: indeed, it is the gravitational field, which is an entity. Since it is possible to define localization with respect to the gravitational field, the substantivalist can also say that “spacetime is an entity that defines localization”.

However, this is an extremely weakened substantivalist position. To what extent is general-relativistic spacetime different from any other arbitrary entity with respect to which we can define a relational localization? We can call “spacetime” anything used to define localization. Newton's acute formulation of substantivalism contains a precise characterization of “space” [Newton, 1962]:

“... So it is necessary that the definition of places, and hence of local motion, be referred to some motionless thing such as extension alone or “space”, *in so far as space is seen to be truly distinct from moving bodies.*”

(My italic.) The characterizing feature of space, according to this substantivalist manifesto, is to be “truly distinct from moving” bodies. In modern terms and after the Faraday and Maxwell conceptual revolution, I believe this can only be translated as being “truly distinct from dynamical entities such as particles or fields”. This is *not* the case for the spacetime of GR. The modern substantivalist can give up Newton's strong substantivalism (“spacetime is a non-dynamical entity”) for the much weaker thesis “we call spacetime the gravitational field, which is a dynamical entity”. But then what is the difference between this position and the relationalist one, if not just a choice of words? To be sure, general relativistic relationalism doesn't fit comfortably with traditional relationalism either. E.g. observables of GR, conceived as coincidence quantities are non-substantial in that they don't require spacetime points to support them. But neither are they relational in the traditional sense of involving relations between “material” bodies or events in their histories.

The traditional substantivalist-relational alternative was formulated before the Faraday-Maxwell conceptual revolution, without taking the existence of the *fields* into account. After Faraday and Maxwell, we understand the world also in terms of a new set or dynamical entities, the fields. Once we accept the existence of the fields, and Einstein's discovery that Newton's space is one of the fields, the distinction between substantivalism and relationalism is largely reduced to mere semantics.

When two opposite positions in a long-standing debate have come so close that their distinction is reduced to semantics, one can perhaps say that the issue is resolved. In this sense, it may be argued that GR has solved the long-standing issue of the relational versus substantivalist interpretation of space.

4.2 Background independence

Is QM compatible with the general relativistic notions of space and time sketched above? It is, but a sufficiently general formulation of QM must be used. For instance, the

Schrödinger picture is only viable for theories where there is a global observable time variable t ; this conflicts with GR, where no such variable exists. Therefore the Schrödinger picture makes little sense in a background independent context. But formulations of QM have been proposed that are more general than the Schrödinger picture. See for instance [Hartle, 1995] and [Rovelli, 2004]. Formulations of this kind are sometimes denoted “generalized quantum mechanics”, although they might be called “quantum mechanics” in the same sense in which “classical mechanics” is used to designate formalisms with different degrees of generality, such as Newton's, Lagrange's, Hamilton's or symplectic mechanics.

On the other hand, most of the conventional machinery of perturbative QFT is profoundly incompatible with the general relativistic framework. There are many reasons for this: (i) The conventional formalism of QFT relies on Poincaré invariance. In particular, it relies on the notion of energy and on the existence of the nonvanishing hamiltonian operator that generates unitary time evolution. The vacuum, for instance, is the state that minimizes the energy. But, in a general relativistic theory there is, in general, no global Poincaré invariance, no general notion of energy and no nonvanishing hamiltonian operator. (ii) At the roots of conventional QFT is the physical notion of particle. The theoretical experience with QFT on curved spacetime [Fulling, 1989] and on the relation between acceleration and temperature in QFT [Wald, 1994] indicates that in a generic gravitational situation the notion of particle can be quite delicate. (iii) Consider a conventional renormalized QFT. The physical content of the theory can be expressed in terms of its n -point functions $W(x_1, \dots, x_n)$. We expect the n -point functions to be invariant under the invariances of the theory. In a general relativistic theory, invariance under an arbitrary coordinate transformation $x \rightarrow x' = x'(x)$ implies immediately that the n -point functions must satisfy

$$(15) W(x_1, \dots, x_n) = W(x'_1, \dots, x'_n).$$

Since any set of n (distinct) points $(x_1, \dots, x_n)$ can be transformed into any other set by a generic coordinate transformation, it follows that W is constant! It does depend on its arguments! Clearly we are in a very different framework from conventional QFT. There is a possible escape strategy to circumvent these difficulties: write the gravitational field as the sum of two terms, as in equation (1), and assume that spacetime and causal relations are defined by the first term, rather than by the full gravitational field. This escape strategy brings back a background spacetime. A formulation of QG that does *not* take this escape strategy, and thus maintains the full symmetry of GR, is called *background independent*.

The divide

Different research directions are oriented by different evaluations given to the general relativistic spacetime conceptual revolution discussed above in Section 4.1. If this conceptual revolution is taken seriously, and understood as a feature of the world that we have learned, the problem of QG becomes the problem of understanding how to define and interpret a background independent QFT. This point of view orients a large part of the research in loop [quantum gravity](#) and similar approaches. Not surprisingly, this line of research is more strongly influenced by the GR research tradition. On the other hand, if the GR conceptual shift is viewed as accidental, the motivation for developing QG comes more from other open problems such as the problem of the unification (see below). One argument often presented for this point of view is that since QG affects microphysics, we can always choose a scale which is sufficiently small to

disregard macroscopic curvature effects and sufficiently large to disregard QG effects. At this scale the world is Lorentz invariant. Therefore in QG we can always assume the existence of an asymptotic Lorentz invariant region. This suggests that we can use techniques associated with asymptotic Lorentz invariance. This line of thinking, predominant in the string community, is more influenced by the particle-physics tradition, which is deeply wedded to Poincaré invariance and which has mostly neglected gravity throughout the twentieth century.

The cultural divide is sometimes very strong, in spite of repeated efforts to fill the gap. Both sides feel that the other side is incapable of appreciating something basic and essential: the structure of QFT as it has been understood in half a century of investigation, for the particle-physics side; the novel physical understanding of space and time that has appeared with GR, for the relativity side. Both sides expect that the other's point of view will turn out, at the end of the day, to be not very relevant. One side because GR is only a low energy limit of a much more complex theory, and thus cannot be taken too seriously as an indication about the deep structure of Nature. The other, because the experience with QFT is on a fixed metric spacetime, and thus is irrelevant in a genuinely background independent context.

4.3 The nature of time

Much has been written about the fact that the main equation of nonperturbative QG, namely the Wheeler-DeWitt equation 5 does not contain the time variable t . This presentation of the “problem of time in QG”, however, is misleading, since it confuses the aspect of the problem that is specific to QG and the one which is already present in classical GR. Indeed, classical GR can be entirely formulated in the Hamilton-Jacobi formalism in terms of equation 4, where no time variable appears either.

In the classical general-relativistic context, the notion of time differs strongly from the one used in the special-relativistic context (and even more strongly from the one used in the pre-relativistic context). In the pre-relativistic context, following Newton, we assume that there is a universal physical variable t , measured by clocks, such that all [physical phenomena](#) can be described in terms of evolution equations in the independent variable t . In the special-relativistic concept, this notion of time is weakened. Clocks do not measure an universal time variable, but rather a proper time elapsed along inertial trajectories. If we fix a Lorentz frame, however, we can still describe all physical phenomena in terms of evolution equations in the independent variable x^0 , even though this description hides the covariance of the system.

In the general relativistic context, we must distinguish two kinds of problems, that are often improperly confused. First, we can consider the problem of the dynamics of matter interacting with a given gravitational field, or, equivalently, on a given spacetime geometry. In this case, the fixed gravitational field still determines the value of the proper time τ elapsed along any (timelike) spacetime trajectory, measured by a clock moving along that trajectory. That is, a given gravitational field determines a local notion of time.

A distinct problem is given by the dynamics of the gravitational field itself, or by the interacting dynamics of gravity and matter. In this case, there is no external time variable that can play the role of observable independent evolution variable. The field equations are written in terms of an evolution parameter, which is the time coordinate x^0 , but this coordinate, as explained above in section 4.1, does not correspond to anything observable. In general, the proper time τ along spacetime trajectories also

cannot be used as an independent variable, as τ is a complicated non-local function of the gravitational field itself. Therefore, properly speaking, GR does not admit a description as a system evolving in terms of an observable time variable. This is particularly evident in the Hamilton-Jacobi formulation (4) of GR. This does not mean that GR lacks predictivity. Simply put, what GR predicts are relations between partial observables, which cannot in general be represented as dependence of dependent variables on a preferred independent time variable.

To be sure, the ontological status of the time variable t is far from being straightforward in Newtonian physics either. In Newtonian physics we describe the world in terms of physical variables $A(t)$, $B(t)$, ... evolving in t . One may notice that in a sense we never directly access t , but only physical variables A , B ..., since the clock devices used to measure t are themselves physical systems with an observable time-dependent variable $C(t)$, such as the position of the clock's hand. Therefore, what we actually observe is always the relative evolution of observable variables $A(C)$, $B(C)$, $A(B)$... and never t itself. Newton makes this point clearly in the *Principia*, but also observes that the direct mathematicization of the apparent motions $A(C)$, $B(C)$, $A(B)$... becomes greatly simplified by hypostatizing the existence of t , and expressing all evolution in terms of t . This of course works excellently in the nonrelativistic and nongravitational context. But it is not illogical that Newton's strategy might fail in certain regimes. And in fact it fails in the relativistic gravitational regime, where no universal t can be introduced, and we can only describe the relative dependence of observable quantities. This is what happens in GR.

In a sense, any partial observable variable can be chosen as the independent one in GR. In general, none has the idealized properties assumed by the Newtonian time t , which grows monotonically irrespectively of the state of the system. For instance, in a closed cosmology the volume a of the universe and the proper time t_c since the Big Bang, along a galaxy worldline, are often used as independent variables. But a behaves badly if the Universe begins recontracting, and t_c is only defined in the approximation in which the Universe is assumed to be homogeneous (what is the value of t_c if two galaxies with different proper time from the big bang meet?)

Such a weakening of the notion of time in classical GR is rarely emphasized, because, after all, in classical physics we may disregard the full dynamical structure of the dynamical theory and consider only a single solution of its equations of motion. As mentioned, a single solution of the GR equations of motion determines a spacetime, where a notion of proper time is associated to each timelike worldline. In the quantum context, on the other hand, there is no single spacetime, as there is no trajectory for a quantum particle, and the very concept of time becomes fuzzy.

Attitudes towards the problem of time

Different attitudes can be found in the literature with regard to the problem of time. For technical overviews and references (not completely up to date), see for instance [Isham, 1992; Kuchar, 1992].

As already mentioned, a considerable part of QG research disregards the issue, and maintains that [Minkowski space](#), Poincaré invariance, with its associated notion of time evolution (as a subgroup of the Poincaré group), should not be abandoned in building QG, notwithstanding the features of GR.

Other authors maintain that even if Poincaré invariance is lost in GR and the notion of time becomes more complex, still the idea that the world exists in time, and that its

description is the description of systems evolving in time, is a primary notion that we cannot renounce.

Some of these authors have proposed minor modifications of GR, capable of reintroducing a fundamental notion of observable time evolution in the theory. One possibility is to choose a preferred gauge-fixing, in which diffeomorphism invariance is partially broken, and the time coordinate is gauge fixed to be equal to some function of the gravitational field. An example is York time, defined as the trace of the extrinsic curvature of a spacelike surface. Alternatively, the dynamics of GR can be modified, to get a theory with an independent time parameter.

Others accept in full the challenge presented by GR of trying to conceptualize the world in the absence of a fundamental notion of time and time evolution, as illustrated in the following section.

Physics without space and time?

An illustrative example of how a formulation of mechanics might not use space and time as independent variables is provided by the following proposal (see [Rovelli, 2004], Chapter 4 and 6). Consider a finite spacetime region R bounded by a closed three-dimensional surface σ . Let (φ, g) represent the value of all fields, including the gravitational field g , on Σ , and let (P_φ, P_g) represent the normal derivative of the fields out of Σ . In principle, all predictions of classical GR can be expressed as constraints on the possible values that the set $(\varphi, g), (P_\varphi, P_g)$ can take. Similarly, in principle all the predictions of QG can be expressed in terms of the probability amplitude $W(\varphi, g)$ of measuring the fields (φ, g) . This is a generalization of Feynman's observation that the quantum dynamics of a particle is contained in the propagator $W(x', t'; x, t)$.

Diffeomorphism invariance implies that $W(\varphi, g)$ does not depend on the way Σ is imbedded into M . In other words, the entire quantitative spatial and temporal dependence is encoded into the dependence of $W(\varphi, g)$ on the gravitational field g . If, for instance, we identify Σ with the surface of the initial, final and boundary values of a scattering experiment, then it is only the value of the gravitational field on the boundary that determines the time lapses between the initial and final surfaces. Recall indeed that in GR spatial distances and temporal intervals are functions of the gravitational field. $W(\varphi, g)$ can then be used in principle to determine all possible probabilistic predictions regarding the experiment, without using independent spatial or temporal variables.

In order to understand the quantum gravitational field, some of the emphasis on geometry should probably be abandoned. Geometry represents well the classical gravitational field, not quantum spacetime. This is not a betrayal of Einstein's legacy: on the contrary, it is a step in the direction of "relativity" in the precise sense meant by Einstein. The key conceptual difficulty of QG may therefore be to find a way to understand the physical world in the absence of the familiar stage of space and time. What might be needed is to free ourselves from the prejudices associated with the habit of thinking of the world as "inhabiting space" and "evolving in time".²

Whether it is logically possible to understand the world in the absence of fundamental notions of time and time evolution, and whether this may be consistent with our experience of the world is an open question.

Unitarity

Absence of a fundamental notion of time evolution implies in particular that there is no unitary time evolution in the theory. Absence of unitarity is viewed with great suspicion

by many physicists coming from the high energy tradition, where the requirement of unitarity has repeatedly played a major historical role. The argument is often put forward that a probabilistic theory without unitary time evolution is inconsistent. This is not correct, since inconsistency follows from lack of unitarity in the presence of a standard time evolution, and not in the absence of it. If, for instance, we describe the evolution of the universe using the volume of the universe a as independent variable, there is no reason to require the probability for the universe to exist to be unit at all a . Indeed, there is a finite probability that the universe reach only a maximum value of a and then re contracts. On the other hand, the consistency of a probabilistic interpretation of QM in a context in which evolution is not expressed in terms of an external variable t is still unclear.

Spacetime algebra as a powerful tool for electromagnetism

Justin Dressel, ... Franco Nori

1.2 Insights from the spacetime algebra approach

To orient the reader, we summarize a few of the interesting insights here that will arise from the spacetime algebra approach. These lists indicate what the reader can expect to understand from a more careful reading of the longer text. Note that more precise definitions of the quantities mentioned here are contained in the main text.

The Clifford product for spacetime algebra is initially motivated by the following basic benefits of its resulting *algebraic structure*:

- The primary reference-frame-independent objects of [special relativity](#) (i.e., scalars, 4-vectors, bivectors/anti-symmetric rank-2 tensors, pseudo-4-vectors, and pseudoscalars) are unified as distinct grades of a *single object known as a multivector*. An element of grade k *geometrically* corresponds to an oriented surface of dimension k (e.g., 4-vectors are line segments, while bivectors are oriented plane segments).

- The associative Clifford product combines the dot and wedge vector-products into a *single and often invertible product* (e.g., for a 4-vector $a^{-1}=a/a^2$).

- The symmetric part of the Clifford product is the *dot product* (Minkowski metric): $a \cdot b = (ab + ba)/2$. Thus, the square of a vector is its scalar pseudonorm $a^2 = \epsilon a|a|^2$ with signature $\epsilon a = \pm 1$.

- The antisymmetric part of the Clifford product is the *wedge product* $a \wedge b = (ab - ba)/2$ (familiar from differential forms), which generalizes the 3-vector cross product ($\times$).

- The sign ambiguity of the *spacetime metric signature* (dot product) is fixed to $(+, -, -, -)$ from general considerations that embed spacetime into a larger sequence of (physically meaningful) nested Clifford subalgebras.

From this structure we obtain a variety of useful and enlightening *mathematical unifications*:

The *Dirac matrices* γ_μ (usually associated with quantum mechanics) appear as a matrix representation of an orthonormal basis for the 4-vectors in spacetime algebra, emphasizing that they are not intrinsically quantum mechanical in nature. The matrix product in the matrix representation simulates the Clifford product. One does *not* need this matrix representation, however, and can work directly with γ_μ as purely algebraic 4-vector elements, which dramatically simplifies calculations in practice.

The *Dirac differential operator* $\nabla = \sum_\mu \gamma_\mu \partial_\mu$ appears as the proper vector derivative on spacetime, with *no* matrix representation required.

The usual 3-vectors from nonrelativistic electromagnetism are *spacetime bivectors* that depend on a particular choice of inertial frame, specified by a timelike unit vector γ_0 . A unit 3-vector $\sigma \rightarrow i = \gamma_i \gamma_0 = \gamma_i \wedge \gamma_0$ that is experienced as a spatial axis by an inertial observer thus has the geometric meaning of a *plane-segment* that is obtained by dragging the spatial unit 4-vector γ_i along the chosen proper-time axis γ_0 .

The *Pauli matrices* are a matrix representation of an orthonormal basis of relative 3-vectors $\sigma \rightarrow i$, emphasizing that they are also not intrinsically quantum mechanical in nature. The matrix product in the matrix representation again simulates the Clifford product.

Factoring out a particular timelike unit vector γ_0 from a 4-vector $v = \sum_\mu v_\mu \gamma_\mu = (v_0 + v \rightarrow) \gamma_0$ produces a *paravector* $(v_0 + v \rightarrow)$ as a sum of a relative scalar v_0 and relative vector $v \rightarrow = \sum_i v_i \sigma \rightarrow i$. Thus relative paravectors and proper 4-vectors are *dual* representations under right multiplication by γ_0 .

The usual 3-gradient vector derivative $\nabla \rightarrow = \gamma_0 \wedge \nabla = \sum_i \sigma \rightarrow i \partial_i$ is the spatial part of the Dirac operator in a particular inertial frame specified by γ_0 .

The *d'Alembertian* is the square of the Dirac operator $\nabla^2 = \partial_0^2 - \nabla \rightarrow^2$.

Directed integration can be defined using a Riemann summation on a spacetime manifold, where the measure dx becomes an oriented k -dimensional geometric surface that is represented within the algebra. This integration reproduces and generalizes the standard results from vector analysis, complex analysis (including Cauchy's integral theorems), and *differential geometry*.

All scalar components of the objects in spacetime algebra are *purely real numbers*. Nevertheless, an intrinsic *complex structure* emerges within the algebra due to the geometry of spacetime itself:

The “*imaginary unit*” naturally appears as the pseudoscalar (unit 4-volume) $I = \gamma_0 \gamma_1 \gamma_2 \gamma_3 = \sigma \rightarrow 1 \sigma \rightarrow 2 \sigma \rightarrow 3$, such that $I^2 = -1$. This pseudoscalar plays the role of the scalar imaginary i throughout the *electromagnetic* theory, without the need for any additional *ad hoc* introduction of a complex scalar field.

The *Hodge-star duality operation* from differential forms is simply the right multiplication of any element by $I^{-1} = -I$. This operation transforms a geometric surface of dimension k into its orthogonal complement of dimension $4-k$ (e.g., the Hodge dual of a 4-vector v is its orthogonal 3-volume vI^{-1} , or pseudo-4-vector).

The *quaternion algebra of Hamilton* $(1, i, j, k)$ that satisfies the defining relations, $i^2 = j^2 = k^2 = ijk = -1$ also appears as the (left-handed) set of spacelike planes (bivectors) in a relative inertial frame: $i = \sigma \rightarrow 1I^{-1}$, $j = -\sigma \rightarrow 2I^{-1}$, $k = \sigma \rightarrow 3I^{-1}$. The bivectors $\sigma \rightarrow iI^{-1}$ directly describe the planes in which spatial rotations can occur, which explains why quaternions are particularly useful for describing spatial rotations.

In addition to the complex structure, *Lie group* and *spinor* structures also emerge:

The bivector basis forms the *Lie algebra of the Lorentz group* under the Lie (commutator) bracket relation $[F, G] = (FG - GF)/2$. Thus, bivectors directly generate *Lorentz transformations* when exponentiated.

The *Lorentz group generators* are the 6 bivectors $S_i = \sigma \rightarrow iI^{-1}$ and $K_i = \sigma \rightarrow i$. Thus, writing the 15 brackets of the Lorentz group $[S_i, S_j] = \epsilon_{ijk} S_k$, $[S_i, K_j] = \epsilon_{ijk} K_k$ and $[K_i, K_j] = -\epsilon_{ijk} S_k$ in terms of a particular reference frame produces simple variations of the three fundamental commutation relations $[\sigma \rightarrow i, \sigma \rightarrow j] = \epsilon_{ijk} \sigma \rightarrow kI$ that are usually associated with quantum mechanical spin (using a Pauli matrix representation). Indeed, the bivectors $\sigma \rightarrow iI^{-1}$ are spacelike planes that generate spatial rotations when exponentiated (just as in quantum mechanics), while $\sigma \rightarrow i$ are the timelike planes, and thus generate Lorentz boosts when exponentiated.

The usual 3-vector *cross product* is the Hodge-dual of the bivector Lie bracket: $F \times G = [F, G]I^{-1}$. Thus, the set of commutation relations $[\sigma \rightarrow i, \sigma \rightarrow j] = \epsilon_{ijk} \sigma \rightarrow kI$ between the 3-vectors $\sigma \rightarrow i$ are simply another way of expressing the usual cross-product relations $\sigma \rightarrow i \times \sigma \rightarrow j = \epsilon_{ijk} \sigma \rightarrow k$.

General *spinors* ψ appear as the (closed) even-graded subalgebra of spacetime algebra (i.e., scalars α , bivectors F , and pseudoscalars αI). Lorentz and other group transformations acquire a simplified form as double-sided products with these spinors (e.g., exponentiated generators like $\psi = \exp(-\alpha \sigma \rightarrow 3I - \phi I) = [\cos \alpha - \sin \alpha \sigma \rightarrow 3I][\cos \phi - \sin \phi I]$), just as is familiar from unitary transformations in *quantum mechanics* and spatial rotations expressed using quaternions.

All these mathematical benefits produce a considerable amount of *physical* insight about the *electromagnetic theory* in a straightforward way:

The *electromagnetic field* is a bivector field F with the same components $F_{\mu\nu}$ as the usual antisymmetric tensor. This tensor is the corresponding multilinear function $F^-(v, w) = v \cdot F \cdot w = \sum_{\mu\nu} v_\mu w_\nu F_{\mu\nu}$ that contracts its two 4-vector arguments (v and w) with the bivector F .

The electromagnetic field is an *irreducibly complex* object with an intrinsic phase $F = f \exp(\phi I)$. This phase necessarily involves the intrinsic pseudoscalar (unit 4-volume) I of spacetime, and is intimately related to the appearance of *electromagnetic waves* and *circular polarizations*, with no need for any *ad hoc* addition of a complex scalar field.

The continuous *dual (electric–magnetic exchange) symmetry* of the vacuum field is a $U(1)$ internal gauge-symmetry (phase rotation) of the field: $F \mapsto F \exp(\theta I)$. This symmetry produces the conservation of helicity via Noether's theorem.

Bivectors decompose in a relative inertial frame into a complex pair of 3-vectors $F = E \rightarrow + B \rightarrow I$, which clarifies the origin of the *Riemann–Silberstein vector*. Both real and imaginary parts in a particular frame are thus physically meaningful. Moreover, the geometric properties of I keep F reference-frame-independent, even though the decomposition into relative fields $E \rightarrow = (F \cdot \gamma_0) \gamma_0$ and $B \rightarrow = (F \wedge \gamma_0) \gamma_0$ still implicitly depends upon the chosen proper-time axis γ_0 in the relative 3-vectors $\sigma \rightarrow = i = \gamma_i \gamma_0$ that form the basis for $E \rightarrow$ and $B \rightarrow$.

All of *Maxwell's equations in vacuum* reduce to a single equation: $\nabla F = 0$.

All of *Maxwell's equations with sources* (both electric and magnetic) also reduce to a single equation: $\nabla F = j$, where $j = j_e + j_m I$ is a complex representation of both types of source, $j_e = (c \rho_e + J \rightarrow) \gamma_0$ and $j_m = (c \rho_m + J \rightarrow m) \gamma_0$.

The scalar *Lorentz invariants* of the electromagnetic field are the invariant parts of its square: $F^2 = (|E \rightarrow|^2 - |B \rightarrow|^2) + 2(E \rightarrow \cdot B \rightarrow) I$.

A *circularly polarized plane wave* is intrinsically complex with the simple exponential form $F(x) = (s k) \exp[\pm(k \cdot x) I]$, with spacelike unit vector $s = E \rightarrow \cdot \gamma_0$, coordinates $x = (ct + x \rightarrow) \gamma_0$, and null wavevector $k = (\omega/c + k \rightarrow) \gamma_0$ such that $k^2 = |\omega/c|^2 - |k \rightarrow|^2 = 0$ is the usual dispersion relation. The sign of I corresponds to the invariant handedness (i.e., *helicity*) of the wave. Expanding the exponential in the relative frame γ_0 yields $F = E \rightarrow + B \rightarrow I$ with the relative fields $E \rightarrow = E \rightarrow \cdot \gamma_0 \cos(k \rightarrow \cdot x \rightarrow - \omega t/c) \pm k \rightarrow \times E \rightarrow \cdot \gamma_0 \sin(k \rightarrow \cdot x \rightarrow - \omega t/c)$ and $B \rightarrow = E \rightarrow \cdot \gamma_0 \sin(k \rightarrow \cdot x \rightarrow - \omega t/c) \mp k \rightarrow \times E \rightarrow \cdot \gamma_0 \cos(k \rightarrow \cdot x \rightarrow - \omega t/c)$, with unit vector $\kappa \rightarrow = k \rightarrow / |k \rightarrow|$ indicating the propagation direction.

The *vector-potential* representation is $F = \nabla z = (\nabla \wedge a_e) + (\nabla \wedge a_m) I$, where $z = a_e + a_m I$ is a complex representation of both electric $a_e = (\phi_e + A \rightarrow) \gamma_0$ and magnetic $a_m = (\phi_m + C \rightarrow) \gamma_0$ 4-vector potentials, each satisfying the Lorenz–FitzGerald gauge conditions $\nabla \cdot a_e = \nabla \cdot a_m = 0$. Maxwell's equation then has the simple wave equation form $\nabla^2 z = j$ with the correspondingly complex source current $j = j_e + j_m I$.

A *transverse and gauge-invariant bivector potential* representation can be defined in a particular inertial frame $Z = z \perp \gamma_0 = A \rightarrow \perp - C \rightarrow \perp I$, where $F = (\nabla Z) \gamma_0$. This complex potential appears in the definition of the conserved optical helicity.

The complex scalar *Hertz potential* $\Phi = \Phi_e + \Phi_m I$ for vacuum fields appears as $Z = (\nabla \rightarrow \times \Pi \rightarrow) I \Phi$ with a chosen unit direction vector $\Pi \rightarrow$, and satisfies $\nabla^2 \Phi = 0$.

The proper *Lorentz force* is $d(mw)/d\tau = F \cdot (qw) = \langle F(qw) \rangle \cdot 1$, where w is a proper 4-velocity of a particle with charge q and mass m .

Making the charge q complex with a dual-symmetry phase rotation $q \mapsto qe^{\theta I} = q_e + q_m I$ produces an equivalent *magnetic monopole* description using the corresponding phase-rotated field $F \mapsto Fe^{\theta I}$. The proper Lorentz force that includes these *magnetic monopoles* is still $d(mw)/d\tau = \langle F(qw) \rangle \cdot 1$. Choosing electric sources is an arbitrary convention that essentially fixes this duality gauge freedom and *breaks the dual symmetry* of the fields.

The *symmetric (Belinfante) energy–momentum tensor* is a bilinear function of the electromagnetic field and a chosen proper-time direction γ_0 that has a simple quadratic form: $T^{\rightarrow} \text{sym}(\gamma_0) = F \gamma_0 \tilde{F} / 2 = (E \rightarrow + B \rightarrow I)(E \rightarrow - B \rightarrow I) \gamma_0 / 2 = (\varepsilon + P \rightarrow) \gamma_0$. This tensor recovers the usual *energy density* $\varepsilon = (|E \rightarrow|^2 + |B \rightarrow|^2) / 2$ and Poynting vector $P \rightarrow = E \rightarrow \times B \rightarrow$ in the relative frame γ_0 , and has the same invariant mathematical form as the symmetric energy–momentum current for the Dirac theory of electrons.

The corresponding (Belinfante) *angular momentum tensor* is a wedge product $M^{\rightarrow} \text{sym}(\gamma_0) = x \wedge T^{\rightarrow} \text{sym}(\gamma_0) = [ex \rightarrow - (ct)P \rightarrow] + x \rightarrow \times P \rightarrow I - 1$ of a radial coordinate x with the energy–momentum tensor. The resulting angular momentum is a *bivector* that includes both boost and spatial-rotation angular momentum, which are distinguished by the extra factor of I in the spatial-rotational part (exactly as $\sigma \rightarrow iI - 1$ indicates a plane of rotation, while $\sigma \rightarrow i$ indicates a boost plane).

The *dual-symmetric Lagrangian density* for the vacuum electromagnetic field is the scalar $L_{\text{dual}}(x) = \langle (\nabla z)(\nabla z^*) \rangle \cdot 0 / 2$, which is a simple *kinetic energy* term for the complex vector potential field $z = ae + amI$. This expands to the sum of independent terms for the electric and magnetic vector potentials: $L_{\text{dual}} = \langle (\nabla ae)^2 \rangle \cdot 0 / 2 + \langle (\nabla am)^2 \rangle \cdot 0 / 2$. Each term is identical in form to the traditional electromagnetic Lagrangian that only includes the electric part ae .

The *conserved Noether currents* of the dual-symmetric Lagrangian produce the proper conserved dual-symmetric *canonical energy–momentum tensor, orbital and spin angular momentum tensors*, and the *helicity pseudovector*.

In the presence of only *electric* sources j_e , the *dual symmetry of the Lagrangian is broken*. The symmetry-breaking of this neutral vector boson doublet is entirely

analogous to the boson doublet that is broken in the electroweak theory by the Brout–Englert–Higgs–Guralnik–Hagen–Kibble (BEHGHK, or Higgs) mechanism. According to this analogy, the second independent magnetic vector potential a_μ that appears in the simple dual-symmetric electromagnetic Lagrangian may become related to the neutral Z^0 boson when additional interaction terms of the [Standard Model](#) are included.

CLASSICAL RELATIVITY THEORY

David B. Malament

PROPOSITION 2.

Let $\bar{g}_{ab}$ be a second smooth metric on M with $\bar{g}_{ab} = \omega^2 g_{ab}$. If $\bar{g}_{ab}$ and g_{ab} agree as to which timelike curves can be reparametrized so as to be geodesics, then ω is constant.

The [spacetime](#) metric g_{ab} , we saw, is determined up to a conformal factor, independently, by the set of possible worldlines of massive point particles, and by the set of possible trajectories of light rays. The proposition now makes clear the sense in which it is fully determined (up to a constant) by those sets together with the set of possible worldlines of free massive particles.¹⁶

Our characterization of relativistic spacetimes is extremely loose. Many further conditions might be imposed. For the moment, we consider just one.

(M, g_{ab}) is said to be *temporally orientable* if there exists a continuous timelike vector field τ^a on M . Suppose the condition is satisfied. Then two such fields τ^a and $\hat{\tau}^a$ on M are said to be *co-oriented* if $\tau^a \hat{\tau}_a > 0$ everywhere, i.e. if τ^a and $\hat{\tau}^a$ fall in the same lobe of the null-cone at every point of M . Co-orientation is an equivalence relation (on the set of continuous timelike vector fields on M) with two equivalence classes. A *temporal orientation* of (M, g_{ab}) is a choice of one of those two equivalence classes to count as the “future” one. Thus, a non-zero causal vector ξ^a at a point of M is said to be *future directed* or *past directed* with respect to the temporal orientation T depending on whether $\tau^a \xi_a > 0$ or $\tau^a \xi_a < 0$ at the point, where τ^a is any continuous timelike vector field in T . Derivatively, a causal curve $\gamma: I \rightarrow M$ is said to be *future directed* (resp. *past directed*) with respect to T if its tangent vectors at every point are.

In what follows, we assume that our background spacetime (M, g_{ab}) is temporally orientable, and that a particular temporal orientation has been specified. Also, given events p and q in M , we write $p \ll q$ (resp. $p < q$) if there is a future-directed timelike (resp. causal) curve that starts at p and ends at q .¹⁷

General Relativity: Overview

R. Penrose

Physical Interpretation of the Metric

Some words of clarification are needed, as to the meaning of the metric tensor g_{ab} in [relativity theory](#). In the early discussions by Einstein and others, the spacetime metric tended to be interpreted in terms of little “rulers” placed on a curved manifold. Although this is natural in the Riemannian (positive-definite) case, it is not quite so appropriate for the Lorentzian geometry of spacetime manifolds. An ordinary physical ruler has a spacetime description as a timelike strip, and it does not naturally express the spatial separation between two spacelike-separated events. In order for a ruler to measure such a spacelike separation, it would be necessary for the two events to be simultaneous in the ruler’s rest frame, and for this to be assured, some further mechanism would be needed, such as Einstein’s procedure for ensuring simultaneity by the use of light signals from the two events to be received simultaneously at their midpoint on the ruler. Clearly this complicates the issue, and it turns out to be much preferable to concentrate on temporal displacements rather than spatial ones.

The idea that spacetime geometry should really be regarded as “chronometry,” in this way, has been stressed by a number of distinguished expositors of relativity theory, most notably John L Synge (1956, 1960) and Hermann Bondi (1961, 1964, 1967). Where needed, spatial displacements can then be defined by the use of temporal ones together with light signals. This has the additional advantage that in modern technology, the measurement of (proper) time far surpasses that of distance in accuracy, to the extent that the meter is now defined simply by the requirement that there are exactly 299792458 of them in a light-second! The proper time interval between two nearby events is, indeed, measured by a clock which encounters both events, moving inertially between the two, and very precise atomic and nuclear clocks are now a common feature of current technology. The physical role of the metric g_{ab} is most clearly seen in the formula

$$\tau = \int p q g_{ab} dx^a dx^b$$

which measures the (proper) time interval τ between an event p and a later event q on its world line, the integral being taken along this curve, and where now that curve need not be a geodesic, so that accelerating (noninertial) motion of the clock is allowed. The metric (with choice of signature $+$ $-$ $-$ $-$ so that it is the timelike displacements that are directly provided as real numbers) is very precisely specified by this physical requirement, and this tells us that the pseudo-Riemannian (Lorentzian) structure of spacetime is far from being an arbitrary construction, but is given to us by Nature with enormous precision. (Some theorists prefer to use the alternative spacetime signature $-$ $+$ $+$ $+$, because this more directly relates to familiar Newtonian concepts, these being normally described in spatial terms. The difference is essentially just a notational one, however. It may be remarked that the 2-spinor formalism (*see* Spinors and Spin Coefficients) fits in much more readily with the $+$ $-$ $-$ $-$ signature being used here.) It may be noted, also that this time measure is ultimately fixed by quantum principles and the masses of the elementary ingredients involved (e.g., particle masses) via the Einstein and Planck relations $E = mc^2$ and $E = h\nu$, so that there is a natural frequency associated

with a given mass, via $v = mc^2/h$ (c being the speed of light and h being Planck's constant).

Lorentzian Geometry

P.E. Ehrlich, S.B. Kim

Two-Dimensional Spacetimes

Two-dimensional spacetimes, sometimes termed Lorentz surfaces, are especially tractable because given (M, g) with $\dim M = 2$, then $(M, -g)$ is also a spacetime. Hence, it may be shown that any Lorentzian 2-manifold (M, g) homeomorphic to $\mathbb{R}^2$ may be made geodesically complete (not just nonspacelike geodesically complete) by a conformal change of metric. Also, any simply connected two-dimensional Lorentzian manifold is strongly causal. In Weinstein (1996), an extensive study is made of Lorentz surfaces generally and particularly, of a conformal boundary for such surfaces first given by Kulkarni in 1985.

One of the prettiest classical results linking the geometry and topology of a Riemannian surface is the Gauss–Bonnet theorem. Let (N, g_0) be a [Riemannian manifold](#) of dimension 2 and let P be a polygonal subregion with [piecewise smooth](#) bounding curves c_i , $1 \leq i \leq k$. Let K denote the Gauss curvature of (N, g_0) and κ the [geodesic curvature](#) of the [smooth curves](#) c_i (which vanishes if c_i happens to be a geodesic).

If α_i denote the corresponding interior angles between the successive boundary curves c_i and c_{i+1} , then the Gauss–Bonnet formula over P is

$$[10] \int_P K dA + \int \partial P \kappa ds + \sum i(\pi - \alpha_i) = 2\pi$$

By considering a triangulation of N itself and summing up the corresponding terms in [10], it follows for a compact oriented Riemannian manifold (N, g_0) of dimension 2 that

$$[11] \int_N K dA = 2\pi \chi(N)$$

where $\chi_{(N)}$ denotes the [Euler characteristic](#). Also lurking in the background here is a formula for computing the angle between unit [tangent vectors](#) v, w as

$$[12] \cos \theta = g_0(v, w)$$

In the spacetime setting, different versions of a Gauss–Bonnet formula for subregions of a two-dimensional spacetime (M, g) corresponding to [10] have been given in 1974 by Helzer and in 1984 by Birman and Nomizu. First, the angle computation is a bit trickier for spacetimes than in the Riemannian case; eqn [12] has to be replaced by techniques which use the [hyperbolic functions](#) $\cosh u$ and $\sinh u$ to define the angle u (sometimes called the “hyperbolic angle”) between two unit vectors and then to allow for [null vectors](#). Birman and Nomizu obtained an analog of [10] assuming that the boundary curves for P are successive smooth unit [timelike curves](#):

$$\int \partial P \kappa ds - \int_P K dA + \sum i \theta_i = 0$$

Helzer in his formulation allows the different boundary curves to be either unit timelike, unit spacelike or [null](#) separately. Since the only compact, orientable [smooth surface](#) which admits a spacetime metric is the 2-torus, which has zero Euler characteristic, the Riemannian formula [11] above translates into the uniform constraint on the Gauss curvature of the spacetime:

$$\int_M f K dA = 0$$

Related terms:

- [General Relativity](#)
- [Field Strength](#)
- [Degree of Freedom](#)
- [Flux Density](#)
- [String Theory](#)
- [Gravitational Wave](#)
- [Black Holes](#)
- [Cosmological Constant](#)
- [Gravitational Field](#)
- [Einstein Equation](#)