Spacetime

By Thomas Knierim

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Introduction

"Do not take the lecture too seriously . . . just relax and enjoy it. I am going to tell you what nature behaves like. If you will simply admit that maybe she does behave like this, you will find her a delightful, entrancing thing. Do not keep saying to yourself "But how can it be like that?" because you will get . . . into a blind alley from which nobody has yet escaped. Nobody knows how it can be like that."

(Richard Feynman introducing a lecture about quantum theory)

Natural sciences always had a great influence on philosophy and on the way we see the world. Until the age of the Renaissance there was no clear distinction between philosophy and science. Speculations about physics and astronomy were among the favourite topics of the natural philosophers of antiquity and continued to flourish until the time of Copernicus. The desire to explore the starry heavens and to reveal its secrets is probably as old as mankind itself. However, notable advances in this discipline were made only fairly recently, after the invention of the telescope in the 17th century. This section deals with the accomplishments of 20th century physics in the world of the largest structures, such as galaxies and stars, and that of the smallest structures, such as atoms and particles. We take a closer look at Relativity and Quantum Physics in particular, both of which have given us amazing new insights into what we call creation.

Newton: the three laws of motion.

In the eyes of physics, the world used to be a predictable place. Aristotle and Ptolemy laid the foundation for the scientific understanding of the universe, which remained authoritative for one-and-a-half thousand years. Until the time of Galileo, the Greeks were undisputed in natural science and astronomy. Galileo, Copernicus, and Newton changed this. Isaac Newton (1642-1727) revolutionised physics with his proposition that all bodies are governed by the three laws of motion. The first law of motion states that a body continues in a state of rest or continues to be moving uniformly in a straight line unless a force is applied to the object. The second law states that the force applied to an object is proportional to its mass multiplied by acceleration ($F=ma$). The third law states that for every action there is an equal opposite reaction.

With these three simple laws, Newton created a whole new model of the universe, superseding Ptolemy's model of epicycles. Eighty years before, Galileo (1564-1642) had pointed out that the Earth rotates around the Sun. The mechanics developed by Newton and Galileo provided the basis for 17th to 19th century cosmology. In this view, planets revolved in well-defined orbits around stars, where the rotational force is balanced by the gravitational force. According to the universal law of gravitation, bodies attract each other with a force $F=m1*m2/r^2$, which means that the force increases with mass and decreases (squared) with distance.

Laplace: the mechanistic universe.

Given these natural laws, mankind derived a picture of the universe that accounts neatly for mass, position, and the motion of the celestial bodies while it interprets the latter as dynamic elements of a celestial apparatus, not unlike that of a mechanical apparatus. It is therefore called the mechanistic worldview. It was elaborated in its purest form by Marquis de Laplace (1749-1827) in his writing Mécanique Céleste. The mechanistic view sees the universe as an arrangement in which stars and planets interact with each other like springs and cogs in a clockwork, while God is watching from above. If the initial positions and states of all objects in a mechanically determined universe are known, all events can be predicted until the end of time, simply by applying the laws of mechanics. It was further thought that this kind of knowledge is available only to an omniscient God.

The mechanistic view does not make any statements about the creation of the universe. Things were taken as preestablished by the creator. From a mechanistic standpoint, solar systems like our own are in a delicate balance, because only a slight increase or decrease in mass or velocity of the planets would let the planets either spiral into the Sun or wander into outer space. There had to be a construction plan. There was a necessity for a creator God who initially put balance into the universe. Needless to say that the church was comfortable with this theory, despite the earlier quarrels with Galileo, and in spite of the fact that it generally viewed scientific progress with great suspicion.

Discovery of the speed of light.

In 1676 the Danish astronomer Ole Roemer (1644-1710) announced a remarkable discovery. He observed seasonal variations in the disappearances of Jupiter's moons behind Jupiter. Because the distance between Earth and Jupiter varies with the seasons, while the Earth travels on its path around the Sun, this means that the light from Jupiter's moons travels either shorter or longer distances throughout the year. The changes in Roemer's observation corresponded with the distances between Earth and Jupiter, which implied that the speed of light is finite. Roemer's observation did, however, not directly contradict the mechanistic worldview. In the mechanistic view, light waves travel through the ether, just as sound waves travel through air. - Yet, there was a problem with the concept of "ether". Its existence could never be detected.

At the end of the 19th century, the mechanistic view was in trouble. Astronomers noticed that Mercury's perihelion (the closest point to the Sun in its orbit) changed slightly with every orbit. This observation shattered the notion of immutable orbits. Astronomers tried to solve this problem by predicting a mystery planet they called Vulcan, which would account for the observed gravitational variations. Needless to say that it was never found.

The American physicists Michelson and Morley brought the mechanistic worldview into even more trouble. In an experiment, which was designed to measure the velocity of the Earth, they found that the speed of light is constant, contrary to what they had expected. They found this characteristic of light to be in disagreement with the Galilean velocity addition formula $v'=v1+v2$, which means their observation contradicted classical mechanics.

Einstein changes everything.

At the beginning of the 20th century, a formerly unknown clerk of the Swiss patent office by the name of Albert Einstein thought to himself: "Falling objects don't feel gravity." He imagined what it would be like to ride through space on a beam of light and came to the conclusion that space and time can be visualised as coordinate systems, or "reference frames", relative to the observer. This was the basis for his Relativity Theory. At about the same time, other physicists pondered on equally fundamental problems, which concerned interactions of matter and radiation, but came to totally different conclusions than Einstein. The result of their collective thought, quantum theory, explained the behaviour of subatomic particles.

With this being written in the year 1999 it is safe to say that Relativity was the single most influential physical theory of the 20th century for the way it has changed our view of the universe. Not that other discoveries in physics were less significant, but few of them have been so well received by the general public. Relativity has grabbed people's imagination and sparked discussions in philosophy and religion which last until the present day. Quantum physics, although perhaps more pertinent to daily life, is a close second.

Is causality questioned by modern physics?

Relativity and Quantum Theory have implications on cosmology, epistemology, and metaphysics. We only begin to understand their impact on our traditional ways of seeing the world. How does God fit into our new picture of the universe? Can the stuff the world is made of be explained by physics alone? What is space and time? Does quantum physics contradict causality? To find out more about these questions and to learn about the findings of Einstein, Heisenberg, and others, take a closer look at the fascinating world of modern physics.

Relativity

The notion of relativity is not as revolutionary as many believe. In fact, spatial relativity is part of our everyday experience. Spatial relativity, also called Galilean relativity in honour of Galileo who first formulated the concept of relative motion, is often confused with Einstein's theories. Galileo simply described the fact that an observer in motion sees things differently from a stationary observer, because he has a different spatial coordinate system, or "reference frame" in Relativity speak. It might sound more complicated than it actually is. Consider the following example:

Galilean relativity: the train example (courtesy of Stephen Hawking).

Two people riding on a train from New York to San Francisco play a game of ping-pong in the sport compartment of the train. Lets say, the train moves at 100 km per hour (= 27.8 m/s) and the two players hit the ball at a speed of two meters per second. In the reference frame of the players, the ball moves back and forth at this particular speed. For a stationary observer standing beside the railroad, however, things look quite different. In his reference frame the ball moves at 29.8 m/s when it is played forward in the direction where the train is heading, while it moves at 25.8 m/s in the same direction when it is played backwards. Thus he doesn't see the ball moving backward at all, but always moving towards San Francisco. For an observer in outer space, things look again totally different because of the Earth's rotation, which is opposite to the train's movement; therefore the outer space observer always sees the ball moving East.

Einstein's new concept of Relativity.

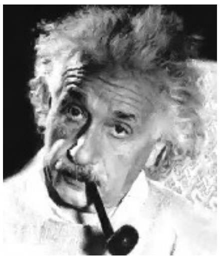
Einstein's Relativity differs from classical relativity, because of the way he looked at time. Before Einstein, people thought time to be absolute, which is to say that one big clock measures the time for the entire universe. Consequently one hour on Earth would be one hour on Mars, or one hour in another galaxy. However, there was a problem with this concept. In an absolute time frame the speed of light cannot be constant. Roemer found that the speed of light is finite and has a certain, quantifiable velocity (usually abbreviated with "c"), which at first implies Galilean relativity. This would mean that while the Earth rotates at a velocity of v, light emitted in the direction of the Earth rotation must be c + v, while light emitted in the opposite direction would travel at c - v, relative to an outside observer.

In 1881, A. Michelson conducted an experiment which proved that this is not the case. With the help of an apparatus that allowed measuring minute differences in the speed of light by changes in the resulting interference patterns, Michelson observed that the speed of light is always the same. No changes whatsoever. The experiment has been repeated later with greater precision by Michelson and E.W. Morley.

Special Relativity published in 1905.

Numerous attempts were made at reconciling these discrepancies, yet they were all unsuccessful, until Einstein solved the dilemma with his famous paper *On the Electrodynamics of Moving Bodies* in 1905, in which he developed his Special Relativity Theory. Special Relativity is an extremely elegant construct that deals with things moving near or at the speed of light. Surprisingly, the new concept of space and time that arises from Relativity is based only on two simple postulates: 1. The laws of physics are the same in all inertial (=non-accelerating) reference frames, and 2. The speed of light in free space is constant.

It is a matter of common experience that one can describe the position of a point in space by three numbers, or coordinates. For the purpose of explaining the relativistic model, Einstein added time as a fourth component to the coordinate system, and the resulting construct is called spacetime. Just as there is an infinite number of 3-D reference frames in Galilean relativity, there is an infinite number of 4-D spacetime reference frames in Einstein's theory. This is to say that Einstein put an end to absolute time. The revolutionary insight lies in the conclusion that the flow of time in the universe does indeed differ depending on one's reference frame.



Albert Einstein (1879-1955)

German physicist Albert Einstein published his papers on Relativity Theory between 1905 and 1916. He became internationally noted after 1919 and was awarded the Nobel Prize in 1921. Einstein emigrated to the USA when Hitler came to power in Germany.

Einstein: "Relativity teaches us the connection between the different descriptions of one and the same reality."

In his usual humble way, Einstein explained how he reinvented physics: "I sometimes ask myself how it came about that I was the one to develop the theory of Relativity. The reason, I think, is that a normal adult stops to think about problems of space and time. These are things which he has thought about as a child. But my intellectual development was retarded, as a result of which I began to wonder about space and time only when I had already grown up." On Relativity, he said: "Relativity teaches us the connection between the different descriptions of one and the same reality."

This view of Relativity, that there are different realities, has been picked up unanimously by the public, and hence, has taken on a far greater meaning than that of the original scientific theory, the focus of which was -strictly speaking- on mechanics and electrodynamics. This astonishing success was at least in part due to Einstein's personality. He understood himself as a philosopher as much as a scientist, and he was ready to discuss philosophical issues at any time, particularly matters involving Relativity. The philosophical aspect of Relativity forced people to think differently about the universe. Suddenly, the cosmos was not a God-created clockwork anymore, but a totality of disparate realities with the same basic natural laws.

$E=mc^2$ - Energy equals mass times the speed of light squared.

An outstanding feature of Special Relativity is its mass-energy relation, which is expressed in the well-known formula: $E=mc^2$.

Einstein derived this relation in an attempt to reconcile Maxwell's electromagnetic theory with the conservation of energy and momentum. Maxwell said that light carries a momentum, which is to say that a wave carries an amount of energy. Due to the principle of conservation of momentum, if a body emits energy in the form of radiation, the body loses an equivalent amount of mass that is given by E/c^2. This describes the relation between energy and mass.

According to the conservation principle, in a closed system the sum of mass and its energy equivalent is always the same. The mass-energy relation tells us that any change in the energy level of an object necessarily involves a change in the object's mass and vice-versa. The most dramatic consequences of this law are observed in nature, for example in nuclear fission and fusion processes, in which stars like the Sun emit energy and lose mass. The same law also applies to the forces set free in the detonation of an atomic bomb.

Was Einstein involved in the development of the atomic bomb?

Einstein was not directly involved in the creation of the atomic bomb, as some people assume. His credits are rather being the one who provided the theoretical framework. In 1939, Einstein and several other physicists wrote a letter to President Franklin D. Roosevelt, pointing out the possibility of making an atomic bomb and the peril that the German government was embarking on such a course. The letter, signed only by Einstein, helped lending urgency to efforts in the creation of the atomic bomb, but Einstein himself played no role in the work and knew nothing about it at the time.

General Relativity published in 1916.

Eleven years after *On the Electrodynamics of Moving Bodies*, Einstein published his second groundbreaking work on *General Relativity*, which continues and expands the original theory. A preeminent feature of General Relativity is its view of gravitation. Einstein held that the forces of acceleration and gravity are equivalent. Again, the single premise that General Relativity is based on is surprisingly simple. It states that all physical laws can be formulated so as to be valid for any observer, regardless of the observer's motion. Consequently, due to the equivalence of acceleration and gravitation, in an accelerated reference frame, observations are equivalent to those in a uniform gravitational field.

This led Einstein to redefine the concept of space itself. In contrast to the Euclidean space in which Newton’s laws apply, he proposed that space itself might be curved. The curvature of space, or better spacetime, is due to massive objects in it, such as the Sun, which warp space around their gravitational centre. In such a space, the motion of objects can be described in terms of geometry rather than in terms of external forces. For example, a planet orbiting the Sun can be thought of as moving along a "straight" trajectory in a curved space that is bent around the Sun.

On the following pages we will examine spacetime and other fascinating aspects of Relativity in some detail and see how Relativity leads us to new insights about the structure and the creation of the universe.

Time Dilation

One of the most enthralling aspects of Relativity is its new understanding of time. The term "time dilation" might evoke images of Salvadore Dali's timepieces hanging on twigs, however, time dilation is all but surrealistic. As stated earlier, if the speed of light is constant, time cannot be constant. In fact, it doesn't make sense to speak of time as being constant or absolute, when we think of it as one dimension of spacetime. Special Relativity states that time is measured according to the relative velocity of the reference frame it is measured in. Despite of the simplicity of this statement, the relativistic connection between time and space are hard to fathom. There are numerous ways to illustrate this:

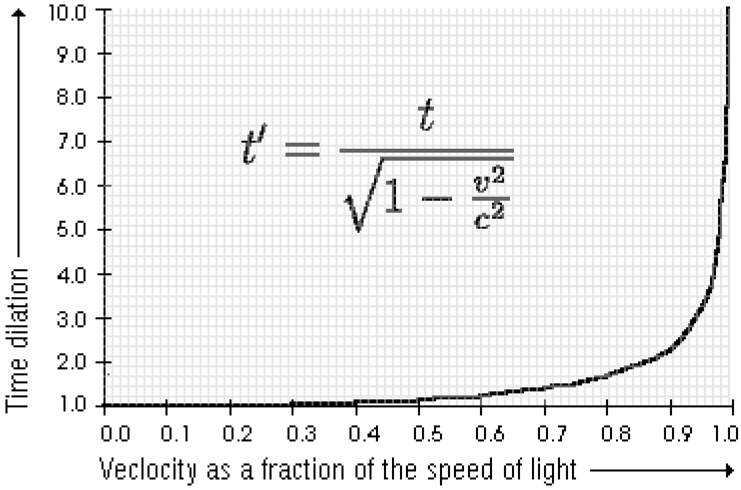
The four dimensions of spacetime.

In Relativity the world has four dimensions: three space dimensions and one dimension that is not exactly time but related to time. In fact, it is time multiplied by the square root of -1. Say, you move through one space dimension from point A to point B. When you move to another space coordinate, you automatically cause your position on the time coordinate to change, even if you don't notice. This causes time to elapse. Of course, you are always travelling through time, but when you travel through space you travel through time by less than you expect. Consider the following example:

Time dilation; the twin paradox.

There are two twin brothers. On their thirtieth birthday, one of the brothers goes on a space journey in a superfast rocket that travels at 99% of the speed of light. The space traveller stays on his journey for precisely one year, whereupon he returns to Earth on his 31st birthday. On Earth, however, seven years have elapsed, so his twin brother is 37 years old at the time of his arrival. This is due to the fact that time is stretched by factor 7 at approx. 99% of the speed of light, which means that in the space traveller’s reference frame, one year is equivalent to seven years on earth. Yet, time appears to have passed normally to both brothers, i.e. both still need five minutes to shave each morning in their respective reference frame.

Time in the moving system will be observed by a stationary observer to be running slower by the factor t':



As it can be seen from the above function, the effect of time dilation is negligible for common speeds, such as that of a car or even a jet plane, but it increases dramatically when one gets close to the speed of light. Very close to c, time virtually stands still for the outside observer.

Time expands, space contracts.

Interestingly, while time expands from the perspective of the stationary observer, space contracts from the perspective of the moving observer. This phenomenon is known as Lorentz contraction, which is exactly the reciprocal of the above time dilation formula: $l'=l*sqr(1-v^2/c^2)$. Thus the space traveller passing by Earth at a speed of 0.99c would see it's shape as an ellipsis with the axis parallel to his flight direction contracted to a seventh of its original diameter. That is of course, if he sees it at all, given the enormous speed. Therefore, space travel is shortened with the velocity of the traveller. A journey to the 4.3 light-years distant Alpha Centauri C, the closest star to our Sun, would take only 7.4 months in a space ship moving at 0.99c.

The effect of time dilation has been experimentally confirmed thanks to very precise caesium clocks that can measure extremely small periods of time. Unfortunately, time dilation is completely outside of human experience, because we have not yet devised a way of travelling at speeds where relativistic effects become noticeable. Even if you spent your whole life in a jet plane that moves at supersonic speed, you would barely win a second over your contemporaries on the ground. And, not even today's astronauts can perceive the Lorentz contraction. Imagine you are a cosmonaut on board of space station Mir, moving at 7700 meters per second relative to Earth. Looking down upon Europe from space, you would see the entire 270 kilometre east to west extent of Switzerland contracted by a mere 0.08 millimetres.

Can we travel at the speed of light?

The hope that one day mankind will be able to travel at near-to-speed-of-light velocities seems farfetched, because of the incredible amounts of energy needed to accelerate a spacecraft to these speeds. The forces are likely to destroy any vehicle before it comes even close to the required speed. In addition, the navigational problems of near-to-speed-of-light travel pose another tremendous difficulty. Therefore, when people say they have to hurry in order to "win time", they probably don’t mean it in a relativistic way.

Kant: Space and time are properties of thought.

The German philosopher, Immanuel Kant (1724-1804), maintained that time and space are a priori particulars, which is to say they are properties of perception and thought imposed on the human mind by nature. This subtle position allowed Kant to straddle the well-known differences about the reality of space and time that existed between Newton and Leibniz. Newton held that space and time have an absolute reality, in the sense of being quantifiable objects. Leibniz held against this that space and time weren't really "things", such as cup and a table, and that space and time have a different quality of being. Kant's position agrees with Newton in the sense that space and time are absolute and real objects of perception, hence, science can make valid propositions about them. At the same time, he agrees with Leibniz by saying that time and space are not "things in themselves," which means they are fundamentally different from cups and tables. Of course, this view of space and time also introduces new problems. It divides the world into a phenomenal (inner) reality sphere and an noumenal (outer) reality sphere. From this academic separation arise many contradictions in epistemology. We will, however, not deal with this particular problem at this point.

Life in a spacetime cubicle.

From Relativity we learn that time and space is seemingly independent of human experience, as the example of time dilation suggests. Since our own perception of time and space is bound to a single reference frame, time appears to be constant and absolute to us. Physics teaches us that this is an illusion and that our perception deceived us within living memory. Thanks to Einstein, we are now able to draw relativistic spacetime diagrams, compute gravitational fields, and predict trajectories through the four-dimensional spacetime continuum. Still, we are hardly able to visualise this spacetime continuum, or deal with it in practical terms, because human consciousness is bound to the human body, which is in turn bound to a single reference frame. We live within the confinements of our own spacetime cubicle.

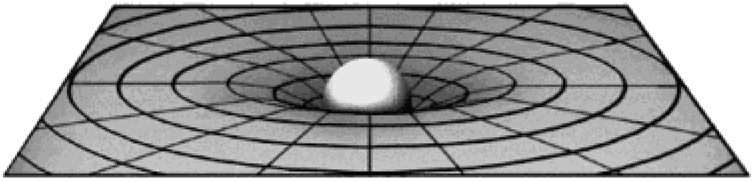
Considering that in Relativity, spacetime is independent of human perception, the Kantian understanding of space and time as a priori particulars seems to be obsolete. They are no longer properties of perception, but properties of nature itself. But, there is more trouble looming for Kant. Relativity stretches the distinction between phenomenal reality, i.e. that which can be experienced, and noumenal reality, i.e. that which is purely intelligible and non-sensory, to a degree where these concepts almost appear grotesque. For example, the question arises, whether time dilation falls into the noumenal or phenomenal category? Since it can be measured, it must be phenomenal, however, since human perception is bound to a single reference frame, it must also be noumenal. The distinction between noumenon and phenomenon is thus blurred and possibly invalidated.

We can attempt to imagine relativistic models with the help of appropriate mathematical models, but cannot experience it directly, at least not until someone builds a near-to-speed-of-light spacecraft. Thanks to Einstein, we are able to look beyond the phenomenal reality of space and time, and we understand that there is more to it than commonsense perception tells us. In a way, Einstein has freed our minds from the spacetime cubicle.

Spacetime

From the preceding reflections on time dilation, we learn that Albert Einstein has overthrown commonsense assumptions about space and time that were valid for centuries. Relative to the observer, distances appear to contract while clocks tick more slowly when moving at velocities close to the speed of light. These are the practical consequences of *Special Relativity*, the work for which Einstein became famous. Einstein did not stop at this point. In 1916, he published his *General Relativity*, which further challenged conventional wisdom. The paper proposed that matter causes spacetime to curve. Gravitation is understood as the warping of spacetime, not a force acting at a distance, as Newton had suggested.

A massive object causes spacetime to curve, which is often illustrated with the picture of a bowling ball lying on a stretched rubber sheet:



Contrary to appearance, the diagram does not depict the three-dimensional space of everyday experience. Instead it shows how a 2-D slice through familiar 3-D space is curved downwards when embedded in flattened hyperspace. We cannot fully envision this hyperspace. Flattening it to 3-D allows us to represent the curvature and helps us visualise the implications of Einstein's General Theory of Relativity.

Gravitation bends light rays.

Since light has no mass, it is not subject to Newton's law of gravity, and hence, in Newtonian physics gravity has no effect on light. If space is curved, however, it follows that a ray of light seemingly moving in a straight line really travels in a curved line following the curvature of space. This is comparable, in some way, to the itinerary of a plane. Because the Earth is a sphere, the shortest path between two points on Earth is described by a geodesic, a curved line. While moving along the geodesic it would appear to the passengers of the plane that they are moving in a straight line, although they are not. Similarly, the light of distant stars travels through the curved geometry of space before it reaches Earth. This proposition is supported by observation.

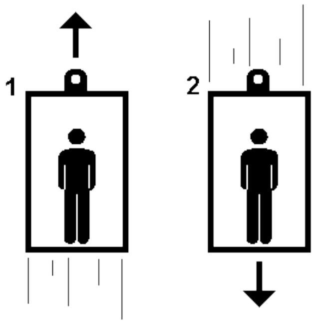
When the light of a star passes close to the Sun, it is deflected by the Sun's gravitational field, which causes it to appear slightly displaced. The star appears to be farther from the Sun than it should be. The displacement has been measured by photographing the apparent position of stars during a solar eclipse and comparing these positions with those observed in the night some time later. Apparent shifts of less than 2 seconds per arc have been measured this way, in close agreement with the predictions of General Relativity. Likewise, the mentioned deviation in the orbit of Mercury when the planet reaches its perihelion (=closest position to the Sun), which is in contradiction with the laws of Newton, can be explained with Einstein's model of curved space.

Gravitation is not a force, but a property of spacetime.

According to Einstein, not only are time and space relative, but the geometry of space is different from what we experience in daily life. Hyperspace is a mathematical construct that we can use to describe gravitational effects in terms of geometry, rather than by the postulation of attracting and repelling forces.

Einstein arrived at this idea by looking at gravity and acceleration. He thought that a falling object does not “feel” any gravitational force, while an object being accelerated does. For this reason, he suggested to equate gravitational mass with inertial mass. He postulated that if a frame of reference is uniformly accelerated relative to a Galilean one, then we can consider it to be at rest by introducing the presence of uniform gravitational field relative to it. This is known as the principle of equivalence.

Principle of equivalence.



The principle says that a uniform acceleration is equivalent to a uniform gravitational field, like the one on Earth. Suppose the elevator in picture (1) is located in space and is accelerated upwards by exactly 32 feet per second squared. The person feels a downward pull that is equivalent to the pull of the gravitational field on Earth. Suppose the elevator in picture (2) is located on Earth and is in the state of free fall. The person in the cabin feels no gravity, because the gravitational field of the Earth is cancelled by the opposite acceleration of the elevator. In both cases, the person cannot tell the difference between the pull of acceleration and gravity, or respectively the weightlessness felt in space and on Earth.

Time dilated by matter.

If acceleration is equivalent to gravitation, it follows that the predictions of Special Relativity must also be valid for very strong gravitational fields. The curvature of spacetime by matter therefore not only stretches or shrinks distances, depending on their direction with respect to the gravitational field, but also appears to slow down the flow of time. This effect is called gravitational time dilation. In most circumstances, such gravitational time dilation is minuscule and hardly observable, but it can become very significant when spacetime is curved by a massive object, such as a black hole.

A black hole is the most compact matter imaginable. It is an extremely massive and dense object in space that is thought to be formed by a star collapsing under its own gravity. Black holes are black, because nothing, not even light, can escape from its extreme gravity. The existence of black holes is not yet firmly established. Major advances in computation are only now enabling scientists to simulate how black holes form, evolve, and interact. They are betting on powerful instruments now under construction to confirm that these exotic objects actually exist.

What happens if an astronaut falls into a black hole?

The gravitational time dilation effect a black hole produces is equal to that of an object moving near the speed of light. For example, an observer far from a black hole would observe time passing extremely slowly for an astronaut falling through the hole's boundary. In fact, the distant observer would never see the hapless victim actually fall in. His or her time, as measured by the observer, would appear to stand still.

From the perspective of the unlucky astronaut, things would, of course, look quite different. After having passed the black hole's event horizon, the point in space from which nothing can escape its pull, there is no way back. While approaching the centre, the gravitational pull on the astronaut's head and feet differs so strongly that the body would be stretched out "like spaghetti" (Stephen Hawking). Hence, it may be a good idea to stay away from black holes, should they actually exist.

Relativity supersedes Aristotle and Newton.

What are the philosophical consequences of Einstein's Relativity Theory? Around 350 BC, Aristotle put forward the view that mechanical objects prefer the state of rest. This proposition was derived from the observation that mechanical systems come to rest if there is no external force sustaining motion. Relativity proves this wrong. The motion of all objects is relative to each other, and it is really a matter of convention to define one reference frame as being at rest. Though this insight comes from Galilean relativity alone, Einstein added that the same applies to the time dimension. Therefore, commonsense notions of congruity and simultaneity do not apply to the processes and events taking place in the large-scale structure of the universe. A lifespan on Earth may be just one second in another galaxy and vice versa. There is a multitude of spacetime reference frames, and a multitude of realities throughout the universe.

Does Relativity disprove empiricism?

The four-dimensional, non-Euclidean spacetime used in relativistic computations defies visualisation and lies beyond human perception. We cannot imagine three-dimensional space being curved, or moving around in a four-dimensional coordinate system. In fact, contemporary physics is only intelligible with the help of mathematics. It cannot be visualised, and it looks as if we have to accept the limitations of our own mind in this regard. This raises an interesting question in epistemology. How do the findings of Relativity fit with David Hume's (1711-1776) famous proposition that all contents of mind, all ideas, concepts, and thoughts are derived from sense experiences? Would Hume be able to uphold his radical empiricism?

Perhaps not. The notion of spacetime in Special and General Relativity is obviously not derived from sense experience. One would also be hard-pressed to explain the making of Relativity merely in terms of derived and recombined sense impressions and associations. Relativity cannot be deduced from empirical judgements, but it is derived from mathematical propositions, or respectively from what Kant had coined "synthetic a priori judgements". Relativity marks a turn in science away from practical laboratory and field study towards purely theoretical fields.

Heraclitus prevails.

Finally, the findings of Einstein may also have put an end to classical controversy between the Greek schools of Heraclitus and Parmenides. The latter philosopher held that all is One and that motion is an illusion, while Heraclitus stated just the opposite, namely that motionlessness is an illusion and that everything is always in a permanent state of motion and change. While the Parmenidean argument may be given some credit for using clever metaphors (from an arrow's perspective the archer is moving away), it is now firmly established that the physical world looks much more Heraclitean than Parmenidean. Even if an object appears to be at rest in a designated reference frame, it still travels through time.

Quantum Theory

Quantum theory evolved as a new branch of theoretical physics during the first few decades of the 20th century in an endeavour to understand the fundamental properties of matter. It began with the study of the interactions of matter and radiation. Certain radiation effects could neither be explained by classical mechanics, nor by the theory of electromagnetism. In particular, physicists were puzzled by the nature of light. Peculiar lines in the spectrum of sunlight had been discovered earlier by Joseph von Fraunhofer (1787-1826). These spectral lines were then systematically catalogued for various substances, yet nobody could explain why the spectral lines are there and why they would differ for each substance. It took about one hundred years, until a plausible explanation was supplied by quantum theory.

Quantum theory is about the nature of matter.

In contrast to Einstein's Relativity, which is about the largest things in the universe, quantum theory deals with the tiniest things we know, the particles that atoms are made of, which we call "subatomic" particles. In contrast to Relativity, quantum theory was not the work of one individual, but the collaborative effort of some of the most brilliant physicists of the 20th century, among them Niels Bohr, Erwin Schrödinger, Wolfgang Pauli, and Max Born. Two names clearly stand out: Max Planck (1858-1947) and Werner Heisenberg (1901-1976). Planck is recognised as the originator of the quantum theory, while Heisenberg formulated one of the most eminent laws of quantum theory, the Uncertainty Principle, which is occasionally also referred to as the principle of indeterminacy.

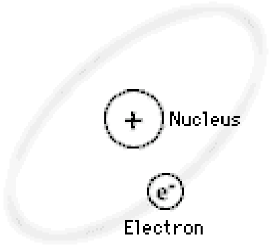
Planck's constant: Energy is not continuous.

Around 1900, Max Planck from the University of Kiel concerned himself with observations of the radiation of heated materials. He attempted to draw conclusions from the radiation to the radiating atom. On basis of empirical data, he developed a new formula which later showed remarkable agreement with accurate measurements of the spectrum of heat radiation. The result of this formula was so that energy is always emitted or absorbed in discrete units, which he called quanta. Planck developed his quantum theory further and derived a universal constant, which came to be known as Planck's constant. The resulting law states that the energy of each quantum is equal to the frequency of the radiation multiplied by the universal constant: E=f*h, where h is 6.63 * 10E-34 Js. The discovery of quanta revolutionised physics, because it contradicted conventional ideas about the nature of radiation and energy.

The atom model of Bohr.

To understand the gist of the quantum view of matter, we have to go back to the 19th century's predominant model of matter. Scientists at the time believed -like the Greek atomists- that matter is composed of indivisible, solid atoms, until Rutherford proved otherwise.

The British physicist Ernest Rutherford (1871-1937) demonstrated experimentally that the atom is not solid as previously assumed, but that it has an internal structure consisting of a small, dense nucleus about which electrons circle in orbits.



Niels Bohr (1885-1962) refined Rutherford's model by introducing different orbits in which electrons spin around the nucleus. This model is still used in chemistry. Elements are distinguished by their "atomic number", which specifies the number of protons in the nucleus of the atom. Electrons are held in their orbits through the electrical attraction between the positive nucleus and the negative electron. Bohr argued that each electron has a certain fixed amount of energy, which corresponds to its fixed orbit. Therefore, when an electron absorbs energy, it jumps to the next higher orbit rather than moving continuously between orbits. The characteristic of electrons having fixed energy quantities (quanta) is also known as the quantum theory of the atom.

The above model bears a striking similarity with the Newtonian model of our solar system. Electrons revolve around the nucleus, just as planets revolve around the Sun. It is therefore not surprising that physicists tried to apply classical mechanics to the atomic structure. The forces between nucleus and electrons were equated with the gravitational forces between celestial bodies. This idea worked quite well for the hydrogen atom, the simplest of all elements, but it failed to explain the behaviour of more complex atoms.

If matter is not infinitely divisible, why should energy be?

The idea that energy could be emitted or absorbed only in discrete energy quanta seemed odd, since it could not be fitted into the traditional framework of physics. The quantum behaviour of electrons in atoms contradicted not only classical mechanics, but also Maxwell's electromagnetic theory, which required it to radiate away energy while orbiting in a quantum energy state. Even Max Planck, who was a conservative man, initially doubted his own discovery. The traditional view was that energy flows in a continuum like a smooth, unbroken stream of water. That there should be gaps between the discrete entities of energy seemed wholly unreasonable. In fact, Planck's idea only gained credence when Einstein used it in 1905 to explain the photoelectric effect. - After all, if matter is not infinitely divisible, why should energy be?

In the course of time, physicists descended deeper into the realm of the atom. Bohr's atom model was remarkably successful in describing the spectrum of the hydrogen atom by using Planck's formula to relate different energy levels of electrons to different frequencies of light radiation. Unfortunately, it did not work well for more complex atoms, and so a more sophisticated theory had to be developed. The problem seemed to be rooted in the assumption that an electron rotates around the nucleus like a massive object revolves around a centre of gravity. De Broglie, Schrödinger, and Heisenberg showed that classical mechanics had to be abandoned in order to describe the subatomic world adequately. In an inference not less dramatic than Planck's discovery of quanta, they stated that particles don't really have a trajectory or an orbit, much less do they behave like a ball that is shot through a corridor or is whirled around on the end of a cord.

The wave-particle duality.

Just as light is thought to have a dual nature, sometimes showing the characteristic of a wave, and sometimes that of a particle (photon), quantum theory attributes a similar dual wave-particle nature to subatomic particles. Electrons that orbit around the nucleus interact with each other by showing interference patterns, not unlike those of wave interference. If the velocity of the electron is thought of as its wavelength, the crests of neighbouring electron waves amplify or cancel each other, thereby creating a pattern that corresponds to Bohr's allowed orbits.

Bohr's model of the atom was superseded by the probability cloud model that describes physical reality better.

The orbital clouds are mathematical descriptions of where the electrons in an atom are most likely to be found, which means the model shows the spatial distribution of electrons. The (simplified) picture to the left shows electron probability clouds in a water molecule. Even cloud models are only approximations. The computation of the actual distribution of electrons in an atom is extremely laborious and the result is too complicated to be illustrated in a single layer 3D model.

About misbehaved electrons, or: the probability cloud model.

The nature of electrons seems odd. Seemingly they exist in different places at different points in time, but it is impossible to say where the electron will be at a given time. At time t1 it is at point A, then at time t2 it is at point B, yet without moving from A to B. It seems to appear in different places without describing a trajectory. Therefore, even if t1 and A can be pinpointed, it is impossible to derive t2 and B from this measurement. In other words: There seems to be no causal relation between any two positions. The concept of causality cannot be applied to what is observed. In case of the electrons of an atom, the closest we can get to describing the electron's position is by giving a number for the probability of it being at a particular place. Moreover, particles have other "disturbing" properties: They have a tendency to decay into other particles or into energy, and sometimes -under special circumstances- they merge to form new particles. They do so after indeterminate time spans. Although we can make statistical assertions about a particle's lifetime, it is impossible to predict the fate of an individual particle.

What does quantum physics say about the universe?

Can we derive any new knowledge about the universe from quantum physics? After all, the entire universe is composed of an unimaginable large number of matter and energy. It seems to be of great importance to understand quantum theory properly in view of the large-scale structure of the cosmos. For example, an interesting question in this context is why the observable matter in the universe is packed together in galaxies and is not evenly distributed throughout space. Could it have to do with the quantum characteristics of energy? Are quantum effects responsible for matter forming discrete entities, instead of spreading out evenly during the birth of the universe? The answer to this question is still being debated.

If cosmological conclusions seem laboured, we might be able to derive philosophical insights from quantum physics. At least Fritjof Capra thinks this is possible when he describes the parallels between modern physics and ancient Eastern philosophy in his book *The Tao of Physics*. He holds that in a way, the essence of modern physics is comparable to the teachings of the ancient Eastern philosophies, such as the Chinese Tao Te Ching, the Indian Upanishads, or the Buddhist Sutras. Eastern philosophies agree in the point that ultimate reality is indescribable and unapproachable, not only in terms of common language, but also in the language of mathematics. That is, science and mathematics must fail at some stage in describing ultimate reality. We see this exemplified in the Uncertainty Principle, which is elucidated in the following section.

Molecules, atoms, and particles are inseparable. All parts interact at all levels.

The oriental scriptures agree in the point that all observable and describable realities are manifestations of the same underlying "divine" principle. Although many phenomena of the observable world are seemingly unrelated, they all go back to the same source. Things are intertwined and interdependent to an unfathomable degree, just as the particles in an atom are. Although the electrons in an atom can be thought of as individual particles, they are not really individual particles, because of the complicated wave relations that exist between them. Hence, the electron cloud model describes the atomic structure more adequately. The sum of electrons in an atom cannot be separated from its nucleus, which has a compound structure itself and can neither be regarded a separate entity. Thus, in the multiplicity of things there is unity. Matter is many things and one thing at the same time.

The Eastern scriptures say that no statement about the world is ultimately valid (“The Tao that can be told is not the eternal Tao.” Tao Te Ching, Verse 1), since not even the most elaborate language is capable of rendering a perfect model of the universe. Science is often compared to a tree that branches out into many directions. The disposition of *physics* is that it follows the tree upward to its branches and leaves, while meta-*physics* follows it down to the root. Whether the branches of knowledge stretch out indefinitely is still a matter of debate. However, it appears that most scientific discoveries do not only answer questions, but also raise new ones.

The German philosopher, FriedrichHegel formulated an idea at the beginning of the 19th century that describes this process. He proposed the dialectic triad of thesis, antithesis, and synthesis, in which an idea (thesis) always contains incompleteness and thus yields a conflicting idea (antithesis). A third point of view (synthesis) arises, which overcomes the conflict by reconciling the truth contained in both, thesis and antithesis, at a higher level of understanding. The synthesis then becomes a new thesis, generates another antithesis, and the process starts over. In the next section, we shall see how 20th century physics embodies Hegel's dialectical principle. We will also take a close look at the philosophical implications of Heisenberg's Uncertainty Principle.

The Uncertainty Principle

At a time when Einstein had gained international recognition, quantum theory culminated in the late 1920's statement of the Uncertainty Principle, which says that **the more precisely the position of a particle is determined, the less precisely the momentum is known in this instant, and vice versa.** The above phrasing of the principle is a succinct version of the mathematically precise uncertainty relation that Heisenberg published in 1927. Since the momentum of a particle is the product of its mass and velocity, the principle is sometimes stated differently, however, its meaning remains the same: The act of measuring one magnitude of a particle, be it its mass, its velocity, or its position, causes the other magnitudes to blur. This is not due to imprecise measurements. Technology is advanced enough to hypothetically yield correct measurements. The blurring of these magnitudes is a fundamental property of nature.

The uncertainty relation describes the "blur" between the measurable quantities of a particle in mathematical terms. Like much of the math in quantum theory, it is not for the faint of heart, which is to say it is completely unintelligible to most people. Therefore we restrict ourselves to a brief account on the underlying ideas and how they developed into the "Copenhagen Interpretation", which Niels Bohr and Werner Heisenberg jointly elaborated as a complete and consistent view of quantum mechanics (the Copenhagen Interpretation refers to Bohr's place of birth).

Heisenberg: "What Schrödinger writes about the visualisability of his theory [...] is crap."

Around 1925 there were two competing mathematical theories that both attempted to explain electron orbits. Matrix mechanics developed by Heisenberg interprets the electron as a particle with quantum behaviour. It is based on sophisticated matrix computations, which introduce discontinuities and quantum jumps. In contrast, wave mechanics developed by Erwin Schrödinger interprets the electron as an energy wave. Because wave mechanics entails more familiar concepts and equations, it quickly gained popularity among scientists.

Schrödinger and Heisenberg were no too fond of each other's competing works. Schrödinger says about matrix mechanics: "I knew of [Heisenberg's] theory, of course, but I felt discouraged, not to say repelled, by the methods of transcendental algebra, which appeared difficult to me, and by the lack of visualisability." Heisenberg's comment on wave mechanics was: "The more I think about the physical portion of Schrödinger's theory, the more repulsive I find it. [...] What Schrödinger writes about the visualisability of his theory 'is probably not quite right,' in other words it's crap."

The Copenhagen Interpretation.

Despite the differences, Schrödinger published a proof in 1926, which showed that the results of matrix and wave mechanics are equivalent; they were in fact the same theory. According to the Copenhagen Interpretation, the wave and particle pictures of the atom, or the visual and causal representations, are "complementary" to each other. That is, they are mutually exclusive, yet jointly essential for a complete description of quantum events. Obviously in an experiment in the everyday world an object cannot be both a wave and a particle at the same time; it must be either one or the other, depending on the situation. In later refinements of this interpretation, the wave function of the unobserved object is a mixture of both, the wave and particle pictures, until the experimenter chooses what to observe in a given experiment.

Werner Heisenberg

The German physicist Werner Heisenberg (1901-1976) received the Nobel Prize in physics in 1932 for his work in nuclear physics and quantum theory. The paper on the uncertainty relation is his most important contribution to physics. Heisenberg impressed his teachers with his ambition and brilliance. He never produced other grades than straight A's, except on one occasion: During his doctorate, professor Wien of the university of Munich gave him an F in experimental physics, because he handled the laboratory equipment clumsily. Reportedly this left Heisenberg so disconcerted that he did not speak to anyone for days. Fate had it that a few years later, Heisenberg demonstrated the very limitations of experimental physics, which unquestionably constituted a setback for its advocates, including Professor Wien.

The observer becomes part of the observed system.

The notion of the observer becoming a part of the observed system is fundamentally new in physics. In quantum physics, the observer is no longer external and neutral, but through the act of measurement he becomes himself a part of observed reality. This marks the end of the neutrality of the experimenter. It also has huge implications on the epistemology of science: certain facts are no longer objectifiable in quantum theory. If in an exact science, such as physics, the outcome of an experiment depends on the view of the observer, then what does this imply for other fields of human knowledge? It would seem that in any faculty of science, there are different interpretations of the same phenomena. More often than occasionally, these interpretations are in conflict with each other. Does this mean that ultimate truth is unknowable?

The results of quantum theory, and particularly of Heisenberg's work, left scientists puzzled. Many felt that quantum theory had somehow "missed the point". At least Albert Einstein did so. He was an outspoken critic of quantum mechanics and is often quoted on his comment regarding the Uncertainty Principle: "The Old One (God) doesn't play dice." He also said: "I like to believe that the moon is still there even if we don't look at it." In particular, Einstein was convinced that electrons do have definite orbits, even if we cannot observe them. In a conversation with Heisenberg he said:

A conversation between Einstein and Heisenberg.

Heisenberg: "One cannot observe the electron orbits inside the atom. [...] but since it is reasonable to consider only those quantities in a theory that can be measured, it seemed natural to me to introduce them only as entities, as representatives of electron orbits, so to speak."

Einstein: "But you don't seriously believe that only observable quantities should be considered in a physical theory?"

"I thought this was the very idea that your Relativity Theory is based on?" Heisenberg asked in surprise.

"Perhaps I used this kind of reasoning," replied Einstein, "but it is nonsense nevertheless. [...] In reality the opposite is true: only the theory decides what can be observed."

(translated from "Der Teil und das Ganze" by W. Heisenberg)

We can easily see the rift between Einstein's intuitive and Heisenberg's empirical approach. Although Einstein's argumentation appears tricky, it is clear that he believes in a reality independent of what we can observe, which is in essence the view of realism. Kant's "thing in itself" comes to mind. - In contrast, Heisenberg believes that reality is what can be observed. If there are different observations, there must be different realities, which depend on the observer. Insofar Heisenberg can be regarded as an advocate of philosophical idealism, which states that the objects of perception are identical with the ideas we have about them. The idealist view denies that any particular thing has an independent real essence outside of consciousness.

Is the moon still there when nobody is looking at it?

The two philosophies seem incompatible at first. Heisenberg is in good company with famous contenders of idealistic positions, such Plato, Schopenhauer, and Husserl, but so is Albert Einstein. If we take Heisenberg's view for granted, strict causality is broken, or better: the past and future events of particles are indeterminate. One cannot calculate the precise future motion of a particle, but only a range of possibilities. Physics loses its grip. The dream of physicists, to be able to predict any future event in the universe based on its present state, meets its certain death.

If we regard reality as that which can be observed by all, we have to find that there is no objective movement of an electron around the nucleus. This viewpoint would imply that reality is created by the observer; in other words: if we take Heisenberg literally, the moon is not there when nobody is looking at it. However, we must consider the possibility that there is a subatomic reality independent of observation and that the electron may have an actual trajectory which cannot be measured. The moon may be there after all. This conflict is the philosophical essence of the Uncertainty Principle.

Relativity and quantum theory are inconsonant up to the present day, despite great efforts in creating a unified theory capable of accommodating both views. After having published his papers on Relativity, Einstein dedicated the rest of his life to working on such a unified field theory, yet without success. The physicists who followed his lead developed a new model called string theory during the 1970s and

1980s. String theory was successful to some extent in providing a mathematical model that integrates the strong and the weak nuclear forces, electromagnetism, and gravitation. In spite of this, it cannot yet be called a breakthrough, because (1) the theory has not been corroborated thoroughly by observational evidence; and (2) there is not one, but five competing string theories. The latter point has recently been addressed by M-theory, a theory that unites existing string theories in 11 dimensions.

The Zen of Quantum Theory.

We shall leave the problem of theoretical unification to the physicists and instead briefly consider a philosophical unification of Relativity and quantum theory. Is this possible? Contemplating the subatomic realm seems like a Zen exercise. The nuclear reality embodies duality and multiplicity, such as is evident in the complicated structure of atoms and particles. It transgresses the narrow world of opposites. We have to realise that in spite of the different parts and components, the subatomic world in actuality is an undivided whole, where the boundary between the observer and the observed is blurred. Object and subject have become inseparable, spatial and temporal detachment is an illusion. When the American physicist J.R. Oppenheimer (1902-1967) describes the structure of probability clouds, he almost sounds like a Zen Master: "If we ask, whether the position of the electron remains the same, we have to say no. If we ask, whether the position of an electron changes with the course of time, we have to say no. If we ask, whether the electron is in a state of rest, we have to say no. If we ask, whether the electron is in motion, we have to say no."

The Universe

In the beginning, the Earth was flat. At least it appeared so to its first observers, hunters and gatherers, and members of early civilisations. Not totally unreasonable, one would think, because the curvature of our planet's surface is not immediately apparent. Yet we know, and it must have been not totally inconceivable even to the archaic tribesmen, that our senses occasionally deceive us. The Earth being flat brings about the problem that it must end somewhere, unless we imagine it to extend infinitely. Infinity is a rather unfathomable conception and, hence, right down to the Middle Ages people were afraid of the possibility of falling off the Earth's boundaries.

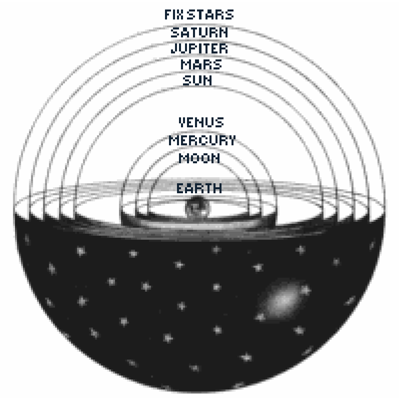
Early cosmogonies.

What lies beyond these boundaries was largely unknown and open to speculation. The starry heavens were a source of endless wonder and inspiration. Peoples from all parts of the world created their own myths, inspired by the skies and the celestial bodies. Their cosmogonies can be seen as an attempt to explain their own place in the universe. Six thousand years ago, the Sumerians believed that the Earth is at the centre of the cosmos. This belief was later carried into the Babylonian and Greek civilisations.

According to the history books, it was the Greeks who first put forward the idea that our planet is a sphere. Around 340 BC, the Greek philosopher Aristotle made a few good points in favour of this theory in *On the Heavens*. First, he argued that one always sees the sails of a ship coming over the horizon first and only later its hull, which suggests that the surface of the ocean is curved. Second, he realised that the eclipses of the Moon were caused by the Earth casting its shadow on the moon. Obviously, the shadow would not always appear round, if the Earth was a flat disk, unless the Sun was directly under the centre of the disk. Third, from their travels to foreign countries, the Greeks knew that the North Star appears higher on the northern firmament and lower in the south. Aristotle explained this correctly with the parallactic shift that occurs when moving between two observation points on a spherical object. Among the Greeks, the heliocentric system was proposed by the Pythagoreans and by Aristarchus of Samos (ca. 270 BC). However, Aristotle dismissed the case for heliocentrism.

Ptolemy's geocentric model of the cosmos.

The influence of Aristotle was significant. Around 150 AD, Claudius Ptolemaeus (Ptolemy) elaborated Aristotle's ideas into a complete cosmological model. He thought that the Earth was stationary at the centre of the universe and that the Sun, the stars, and all planets revolve around it in circular orbits, hence, the model is sometimes referred to as the geocentric system. Ptolemy was aware that the postulation of perfect circular orbits contradicted observation, because the planets' motion, size and brightness varied with time. To account for the observed deviations, he introduced the idea of epicycles, smaller circular orbits around imaginary centres on which planets were supposed to move while describing a revolution around Earth. This enabled astronomers to make reasonably accurate predictions about the movement of the celestial bodies, and consequently the Ptolemaic model was a great success. The system was later adopted by the Christian Church and became the dominant cosmology until the 16th century.



Ptolemy's model of the universe was that of an onion with the Earth at its centre and stars arranged in layers around it. The outer layer was thought to be like a crystal to which the fix stars were attached. The hypothesis of epicycles accounted for the observable deviations.

Copernicus.

In 1514 the Polish astronomer Nicolaus Copernicus (1473-1543) put forward an alternative model, referred to as the heliocentric system, in which the Sun is at the centre of the universe, and all planets, including Earth, revolve around it. The further apart a planet is from the Sun, the longer it takes to complete a revolution. Copernicus said that the ostensible movement of the Sun is caused by the Earth rotating around its north-to-south axis. The heliocentric system got rid of Ptolemy's obscure epicycles, whose main weakness was that they did neither account for the observed backward motion of Mars, Jupiter, and Saturn, nor for the fact that Mercury and Venus never moved more than a certain distance from the Sun. Unfortunately, the Copernican system was not inherently simpler than the geocentric system; and it did not immediately render more accurate calculations of the planet's motion.

Galileo.

The end of the Ptolemaic theory came with the invention of the telescope. With the help of this device, Galileo Galilei (1564-1642) discovered the four largest Jupiter moons. The existence of these moons demonstrated beyond doubt that not all celestial bodies revolve around the Earth, contrary to Ptolemy's theory. Galileo confirmed the Copernican model and thus initiated a scientific revolution of great importance, much to the discontent of the Roman Catholic Church. Unsurprisingly, Galileo struggled with church authorities during much of his lifetime. In 1594 the German astronomer Johannes Kepler (1571-1630) refined the heliocentric model in his book *Mysterium Cosmographicum* by showing that planets move on elliptical, rather than circular orbits. Kepler also prepared the idea of gravity by explaining that the Sun exerts a force on planets that diminishes inversely with distance and causes them to move faster on their orbits, the closer they come to the Sun. This theory finally allowed predictions that matched observations.

Kepler and Newton: The paradox of the collapsing universe.

Kepler's model became the accepted 17th century cosmology, until Isaac Newton further refined Kepler's notion of the forces between celestial bodies. Newton postulated the law of universal gravitation that applied to all bodies, whether in space or on Earth, and he supplied the mathematical foundation for it. According to Newton, bodies attract each other proportionally with their size and inverse proportionally with the square of the distance between them. He went on to demonstrate that according to this law, planets move on elliptical orbits, as previously assumed by Kepler. Unfortunately, one consequence of this theory is that the stars of the universe attract each other and thus must eventually collapse onto each other. Newton was not able to give a plausible explanation for why this did not happen.

To counter this paradox, it was inferred that the universe is infinite in space, and thus contains an infinite number of evenly distributed stars, which would on the whole create a gravitational equilibrium. This assumption, however, would still imply instability. If the balance is disturbed in one region of space, the nearest stars collapse and the gravitational pull of the resulting more massive body draws in the next cluster of stars. Clusters would collapse like a house of cards and eventually draw in the entire universe. Today we know that this is not the case, because the universe is not static as Newton thought. The cosmos is in a state of expansion and therefore, gravitational collapse is prevented.

Is the universe infinite in space and time?

The question of whether the universe has boundaries in time and space has captivated the imagination of mankind since early times. Some would say the universe had existed forever, while others would say that the universe was created and thus had a beginning in time and space. The second thesis immediately raises the question what exists beyond its temporal and spatial bounds. Could it be nothingness? But then, what is nothingness? The absence of matter, or the absence of space and time itself? The German philosopher Immanuel Kant (1724-1804) dealt intensively with this question. In his book *Critique of Pure Reason* he came to the conclusion that the question cannot be answered reliably within the limits of human knowledge, since thesis and antithesis are equally valid. Kant thought instead of time and space as fundamental aspects of human perception.

Big Bang - the birth of our universe.

Fast forward: Despite Kant's doubts thereto, it appears that modern cosmology has answered the above question. The universe we can observe is finite. It has a beginning in space and time, before which the concept of space and time has no meaning, because spacetime itself is a property of the universe. According to the Big Bang theory, the universe began about twelve to fifteen billion years ago in a violent explosion. For an incomprehensibly small fraction of a second, the universe was an infinitely dense and infinitely hot fireball. A peculiar form of energy that we don't know yet, suddenly pushed out the fabric of spacetime in a process called "inflation", which lasted for only one millionth of a second. Thereafter, the universe continued to expand but not nearly as quickly. The process of phase transition formed out the most basic forces in nature: first gravity, then the strong nuclear force, followed by the weak nuclear and electromagnetic forces. After the first second, the universe was made up of fundamental energy and particles like quarks, electrons, photons, neutrinos and other less familiar particles.

About 3 seconds after the Big Bang, nucleosynthesis set in with protons and neutrons beginning to form the nuclei of simple elements, predominantly hydrogen and helium, yet for the first 100,000 years after the initial hot explosion there was no matter of the form we know today. Instead, radiation (light, X rays, and radio waves) dominated the early universe. Following the radiation era, atoms were formed by nuclei linking up with free electrons and thus matter slowly became dominant over energy. It took 200 million years until irregularities in the primordial gas began to form galaxies and early stars out of pockets of gas condensing by virtue of gravity. The Sun of our solar system was formed out of such a pocket of gas in a spiral arm of the Milky Way galaxy roughly five billion years ago. A vast disk of gas and debris swirling around the early Sun gave birth to the planets, including Earth, which is between 4.6 and 4.5 billion years old. This is -in short- the history of our universe according to the Big Bang theory, which constitutes today's most widely accepted cosmological viewpoint.

What speaks in favour of the Big Bang theory?

A number of different observations corroborate the Big Bang theory. Edwin Hubble (1889-1953) discovered that galaxies are receding from us in all directions. He observed shifts in the spectra of light from different galaxies, which are proportional to their distance from us. The farther away the galaxy, the more its spectrum is shifted towards the low (red) end of the spectrum, which is in some way comparable to the Doppler effect. This redshift indicates recession of objects in space, or better: the ballooning of space itself. Today, there is convincing evidence for Hubble's observations. Projecting galaxy trajectories backward in time means that they converge to a high-density state, i.e. the initial fireball.

If two intelligent life forms in two different galaxies look at each other’s galaxy, they perceive the same thing. The light of the other galaxy appears redshifted in comparison to nearer objects. This is caused by ballooning space that stretches the wavelength of emitted light. The magnitude of this effect is proportional to the distance of the observed galaxy.

According to the Copernican cosmological principle, the universe appears the same in every direction from every point in space, or in more scientific terms: The universe is homogeneous and isotropic. There is overwhelming evidence for this assertion. The best evidence is provided by the almost perfect uniformity of the cosmic background radiation. This observed radiation is isotropic to a very high degree and is thought to be a remnant of the initial Big Bang explosion. The background radiation originates from an era of a few hundred thousand years after the Big Bang, when the first atoms where formed. Another piece of evidence speaking in favour of Big Bang is the abundance of light elements, like hydrogen, deuterium (heavy hydrogen), helium, and lithium. Big Bang nucleosynthesis predicts that about a quarter of the mass of the universe should be helium-4, which is in good agreement with what is observed.

Will the universe expand forever?

On basis of our understanding of the past and present universe, we can speculate about its future. The prime question is whether gravitational attraction between galaxies will one day slow the expansion and ultimately force the universe into contraction, or whether it will continue to expand and cool forever. The current rate of expansion (Hubble Constant) and the average density of the universe determine whether the gravitational force is strong enough to halt expansion. The density required to halt expansion (=critical density) is 1.1 * 10^-26 kg per cubic meter, or six hydrogen atoms per cubic meter; the relation "actual density" / "critical density" is called Omega. With Omega less than 1, the universe is called "open", i.e. forever expanding. If Omega is greater than 1 the universe is called "closed", which means that it will contract and eventually collapse in a Big Crunch. In the unlikely event that Omega = 1, the expansion of the universe will asymptotically slow down until it becomes virtually imperceptible, but it won't collapse.

Big Bang - Big Crunch?

Some scientists think it not impossible that the universe is oscillating between eras of expansion and contraction, where every Big Bang is followed by a Big Crunch. Stephen Hawking (born 1942) pointed out the possibility that such an oscillating universe must not necessarily start and end in singularities, i.e. questionable points in spacetime where physical theories, such as General Relativity, break down while energy and density levels approximate infinity. Although everything points towards Big Bang, the future reversal and contraction of the universe is rather uncertain. Big Crunch is at most a hypothesis, because only about 1/100th of the matter needed for Omega=1 can be observed.

In spite of this, galaxies and star clusters behave as if they would contain more matter than we can see. It is almost as if these objects were engulfed by invisible matter. This "dark matter" that cannot be accounted for is one of the open questions in cosmology. Dark matter makes is thought to make up 23% of the universe.

Big Rip!

Today, most cosmologists believe there is not enough matter in the universe to halt and revert expansion. Robert Caldwell of Dartmouth University has recently suggested a third alternative for the fate of the universe. His *Big Rip* scenario is based on astronomical observations made in the late 1990s according to which a mysterious force, labelled dark energy, is responsible for the expansion of the universe. Dark energy makes up 73% of the universe. If the rate of acceleration increases, there will be a point in time at which the repulsive force becomes so strong that it overwhelms gravity and the other fundamental forces. According to Caldwell, this will happen in 20 billion years. "The expansion becomes so fast that it literally rips apart all bound objects," Caldwell explains. "It rips apart clusters of galaxies. It rips apart stars. It rips apart planets and solar systems. And it eventually rips apart all matter." Even atoms would be torn apart in the last 10^{-19} seconds before the end of time. –Whether or not this scenario will become true is to be decided by future research. Until then, the field is open to speculation.

Open Questions

Physics has answered many questions about space, time, and matter. Thanks to technological advances, we have been able to look deeper and deeper into the large-scale structure of the universe and the small-scale structure of matter. From the invention of the telescope to the time of particle accelerators, insight and understanding have grown. Yet, there are still many unsolved mysteries. The contemporary models of matter, space, and time are incomplete and our picture of the world still has holes. Some of today's most challenging questions in physics are:

What is dark matter?

There seems to be a halo of mysterious invisible material engulfing galaxies, which is commonly referred to as dark matter. Scientists infer the existence of dark (=invisible) matter from the observation of its gravitational pull, which causes the stars in the outer regions of a galaxy to orbit faster than they would if there was only visible matter present. Another indication is that we see galaxies in our own local cluster moving towards each other.

The Andromeda galaxy -about 2.2 million light years away from the Milky Way- is speeding toward us at 200,000 miles per hour. This motion can only be explained by gravitational attraction, even though the mass we observe is not nearly great enough to exert that kind of pull. It follows there must be a large amount of unseen mass causing the gravitational pull -roughly equivalent to ten times the size of the Milky Way- lying between the two galaxies.

Astronomers have no idea what the dark matter is that supposedly makes up 23% of all matter in our universe. Black holes and massive neutrinos are two possible explanations. Dark matter must have played an important role in galaxy formation during the evolution of the cosmos. But, even taking into account all known and suspected black holes, there seems to be much more matter out there than we can presently see or extrapolate.

What is dark energy?

Dark energy is perhaps even more mysterious than dark matter. The discovery of dark energy goes back to 1998 when a 10-year study of supernovae took an astonishing turn. A group of scientists had recorded several dozen supernovae, including some so distant that their light had started to travel towards Earth when the universe was only a fraction of its present age. The group's goal was to measure small changes in the expansion rate of the universe, which in turn would yield clues to the origin, structure, and fate of the cosmos. Contrary to their expectation, the scientists found that the expansion of the universe is not slowing, but accelerating.

The acceleration is supposedly due to the anti-gravitational properties of the so-called dark energy. While the exact nature of this energy is presently unknown, scientists agree that dark energy is the dominant constituent of our universe, which means that it is larger than the sum of visible and dark matter. Einstein already postulated an anti-gravitational force at the beginning of the 20th century. He acknowledged that the observed matter would lead to gravitational collapse, and hence, introduced a cosmological constant to bring Relativity into line with observation. After it was discovered by Hubble that the universe is expanding, Einstein called his cosmological constant the greatest blunder of his life.

Yet, at the beginning of the 21st century it seems that anti-gravity is coming back with vengeance. A possible explanation is that the energy content of a vacuum is non-zero with a negative pressure. This negative pressure of the vacuum would grow in strength as the universe expands and it would cause the expansion to accelerate. If the acceleration does not stop, this will lead to the Big Rip scenario suggested by Caldwell, in which the universe will be literally torn apart by the anti-gravitational force in several billion years.

Home did the universe come into being?

Stephen Hawking says in the foreword of *The Cosmos Explained* (Cambridge, July 28, 1997): "At the Big Bang, the universe and time itself came into existence, so that this is the first cause. If we could understand the Big Bang, we would know why the universe is the way it is. It used to be thought that it was impossible to apply the laws of science to the beginning of the universe, and indeed that it was sacrilegious to try. But recent developments in unifying the two pillars of twentieth-century science, Einstein's General Theory of Relativity and the Quantum Theory, have encouraged us to believe that it may be possible to find laws that hold even at the creation of the universe. In that case, everything in the universe would be determined by the laws of science. So if we understood those laws, we would in a sense be masters of the universe."

It is uncertain whether mankind is able to develop such a theory in the near future, and it may be even more questionable whether this knowledge would indeed help us to become masters of the universe, as Stephen Hawking connotes. Obviously it is difficult to speculate on a theory that has not been developed yet. The theory might as well have no practical value at all. The great 20th century physical theories showed us that complexity and abstraction are growing, while intelligibility and practical applicability are decreasing. From a unified physical theory we can expect a more complete picture of matter, space, and time and a better understanding of the beginning of the universe. It may satisfy our curiosity in view of some big philosophical questions. Any practical value beyond this is rather uncertain.

Unified theories: How does gravity fit into the big picture?

The theory of gravity as formulated by Einstein is incompatible with the rules of quantum mechanics. Physicists encounter serious difficulties when trying to construct a quantum version of gravity. In the later years of his life, Einstein tried but failed to devise a theory that unifies gravity with quantum theory. In the 1960s, the weak nuclear force was united with electromagnetism to form the electroweak theory, which was subsequently verified in particle accelerator experiments. The next step is to create a model that unites the other fundamental forces.

Theorists are working on such a model, which they call grand unified theory (GUT). It amalgamates electromagnetism with the weak and strong nuclear interaction, but omits gravity. From GUT we expect the answer to why particles have the masses we observe. Although we observe the masses of electrons, protons, and neutrons generated through what is called "electroweak breaking," we don't know how this breaking mechanism works. GUT should be able to interpret the electroweak breaking process and thus provide an explanation for the mass of a particle.

Beyond GUT, there is a theory that accounts for all four fundamental forces in nature, including gravity. The greatest endeavour of physics is to draw hitherto unrelated and incompatible theories together into a single unified theory. The advantage of such a system is obvious: It would account for all currently known phenomena without leaving theoretical holes and it may point towards future areas of study. It is hypothesised that such a theory could create a new fundamental understanding of nature. String theory, supersymmetry, and M-theory are some candidates currently considered.

Are quarks and leptons actually fundamental, or are they made up of even more fundamental particles?

Presently it is not known whether quarks and leptons are elementary or compound particles. It seems that physicists have become more careful with announcing the fundamentality of particles after having learned that atoms, atom cores, and finally protons and neutrons are divisible. What is more, quarks and leptons are so small that they may be thought of as geometrical points in space with no spatial extension at all. This is perhaps not as miraculous as it first sounds, because after having learned from Rutherford's model that the volume of an atom is mostly made of "empty" space, it would not be too surprising to find out that matter is in fact nothing but empty space.

While the commonly accepted standard model of matter provides a very good description of the phenomena observed in experiments, the model is still incomplete. It can explain the behaviour of particles fairly well, but it cannot explain why some particles exist as they do. For example, it has been impossible to predict the mass of the top quark accurately from theoretical inference until it was determined experimentally. As mentioned before, the standard model of matter does not provide any mathematical model that allows us to calculate the observed mass.

Another question concerns the fact that there are three families of quarks and leptons. Of the three families (or generations) of particles, only the first is stable, namely that of up/down quarks, e-neutrinos, and electrons. There seems to be no need for the other two generations in the natural world, yet they exist. Theoretical physics has no explanation for the existence of the two unstable generations. Likewise, the question why there is hardly any antimatter in the observable universe remains unaccounted for. Since there is an almost perfect symmetry between matter and antimatter, one would expect some regions of the universe to be composed of matter and others of antimatter, yet almost all mass we can observe is composed of conventional matter.

Is our universe unique, or are there many universes?

Andrei Linde at Stanford has brought forward the cosmological model of a multiverse, which he calls the "self-reproducing inflationary universe." The theory is based on Alan Guth's inflation model, and it includes multiple universes woven together in some kind of spacetime foam. Each universe exists in a closed volume of space and time. Linde's model, based on advanced principles of quantum physics, defies easy visualisation. Quite simplified, it suggests quantum fluctuations in the universe's inflationary expansion period to have a wavelike character. Linde theorises that these waves can "freeze" atop one another, thus magnifying their effect.

The stacked-up quantum waves can in turn create such intense disruptions in scalar fields -the underlying fields that determine the behaviour of elementary particles- that they exceed a critical mass and start procreating new inflationary domains. The multiverse, Linde contends, is like a growing fractal, sprouting inflationary domains, with each domain spreading and cooling into a new universe.

If Linde is correct, our universe is just one of the sprouts. The theory neatly straddles two ancient ideas about the universe: that it had a definite beginning, and that it had existed forever. In Linde's view, each particular part of the multiverse, including our part, began from a singularity somewhere in the past, but that singularity was just one of an endless series that was spawned before it and will continue after it.

Will a complete physical model of the world help us to understand ultimate reality? Can we understand ultimate reality at all through science?

Some physicists believe that a complete physical model can explain everything we observe. They hold that once the fundamental laws are known and powerful computers allow us to compute models of the world by applying these laws, we can eventually deduce explanations for all phenomena. In other words, physics can lead us to understanding ultimate reality. Is this really possible?

One may doubt it. Even if we give physicists credit for their remarkable discoveries, we have to realise that their research takes place in an isolated field of knowledge. Physics does not concern itself with issues outside its own domain. For example, the subjects of biology, life, and chemistry, as well as the phenomena of mind and consciousness cannot be explained in physical terms. In addition, the following fundamental questions arise:

1. Physics deals only with what can be observed and measured. A complete physical model must therefore necessarily produce a materialistic view of reality. Although materialists usually deny the possibility that phenomena exist which cannot be measured or somehow quantified, they may actually exist.

2. There are *physical* limits to what can be measured, as demonstrated by the Uncertainty Principle.

3. The materialist view is generally allied with reductionism. Materialists often claim that high-level phenomena, such as biological or psychological phenomena, can be

reduced to physical phenomena. However, this is far from being obvious. For example, there is no generally accepted reductionist theory of consciousness. Reductionism fails in most practical cases. For example, it is practically impossible to describe the process of DNA replication in terms of subatomic properties.

4. Advanced physical models are abstract to the degree of being unintelligible to most people. Modern physics is based on higher mathematics and can hardly be put into common language, much less can it be imagined. The multidimensional worlds of Relativity and string theory, for example, are elusive to plastic imagination. The value of any science depends on how useful its models are for the thoughts and actions of humanity as a whole, hence, its usefulness leans partly on intelligibility.

Frequently Asked Questions

What is light?

Light is a phenomenon that has particle and wave characteristics. Its carrier particles are called photons, which are not really particles, but massless discrete units of energy.

What is the speed of light?

The speed of light is 299,792,458 m/s in a vacuum. The symbol used in Relativity for the speed of light is "c", which probably stands for the Latin word "celeritas", meaning swift.

Is the speed of light really constant?

The speed of light is constant by definition in the sense that it is independent of the reference frame of the observer. Light travels slightly slower in a transparent medium, such as water, glass, and even air.

Can anything travel faster than light?

No. In Relativity, c puts an absolute limit to speed at which any object can travel, hence, nothing, no particle, no rocket, no space vehicle can go at faster-than-light (=superluminal) speeds. However, there are some cases where things appear to move at superluminal speeds, such as in the following examples: 1. Consider two spaceships moving each at 0.6c in opposite directions. For a stationary observer, the distance between both ships grows at faster-than-light speed. The same is true for distant galaxies that drift apart in opposite directions of the sky. 2. Another example: Consider pointing a very strong laser on the moon so that it projects a dot on the moon's service and then moving the laser rapidly towards Earth, so that it points on the floor in front of you. If you accomplish this in less than one second, the laser dot obviously travelled at superluminal speed, seeing that the average distance between the Earth and the Moon is 384,403 km.

What is matter?

The schoolbook definition would be: Matter is what takes up space and has mass. Matter as we know it is composed of molecules, which themselves are built from individual atoms. Atoms are composed of a core and one or more electrons that spin around the core in an electron cloud. The core is composed of protons and neutrons, the former have a positive electrical charge, the latter are electrically neutral. Protons and neutrons are composed of quarks, of which there are six types: up/down, charm/strange, and top/bottom. Quarks only exist in composite particles, whereas leptons can be seen as independent particles. There are six types of leptons: the electron, the muon, the tau and the three types of neutrinos. The particles that make up an atom could be seen as a stable form of locked up energy. Particles are extremely small, therefore 99.999999999999% (or maybe all) of an atom's volume is just empty space. Almost all visible matter in the universe is made of up/down quarks, electrons and (e-)-neutrinos, because the other particles are very unstable and quickly decay into the former.

How fast does an electron spin?

An electron in a hydrogen atom moves at about 2.2 million m/s. With the circumference of the n=1 state for hydrogen being about 0,33x10-9 m in size, it follows that an n=1 electron for a hydrogen atom revolves around the nucleus 6,569,372 billion times in just one second.

Are quarks and leptons all there is?

Not really. Fist of all, quarks always appear in composite particles, namely hadrons (baryons and mesons), then there is antimatter, and finally there are the four fundamental forces.

What is antimatter?

The existence of antimatter was first predicted in 1928 by Paul Dirac and has been experimentally verified by the artificial creation of the positron (e+) in a laboratory in 1933. The positron, the electron's antiparticle, carries a positive electrical charge. Not unlike the reflection in a mirror, there is exactly one antimatter particle for each known particle and they behave just like their corresponding matter particles, except they have opposite charges and/or spins. When a matter particle and antimatter particle meet, they annihilate each other into a flash of energy. The universe we can observe contains almost no antimatter. Therefore, antimatter particles are likely to meet their fate and collide with matter particles. Recent research suggests that the symmetry between matter and antimatter is less than perfect. Scientists have observed a phenomenon called charge/parity violation, which implies that antimatter presents not quite the reflection image of matter.

What are the four fundamental forces?

The four fundamental forces are gravity, the electromagnetic force, and the weak and strong nuclear forces. Any other force you can think of (magnetism, nuclear decay, friction, adhesion, etc.) is caused by one of these four fundamental forces or by a combination of them. Electromagnetism and the weak nuclear force have been shown to be two aspects of a single electroweak force.

What is gravity?

Gravity is the force that causes objects on Earth to fall down and stars and planets to attract each other. Isaac Newton quantified the gravitational force: $F = \text{mass1} * \text{mass2} / \text{distance}^2$. Gravity is a very weak force when compared with the other fundamental forces. The electrical repulsion between two electrons, for example, is some 10^40 times stronger than their gravitational attraction. Nevertheless, gravity is the dominant force on the large scales of interest in astronomy. Einstein describes gravitation not as a force, but as a consequence of the curvature of spacetime. This means that gravity can be explained in terms of geometry, rather than as interacting forces. The General Relativity model of gravitation is largely compatible with Newton, except that it accounts for certain phenomena such as the bending of light rays correctly, and is therefore more accurate than Newton's formula. According to General Relativity, matter tells space how to curve, while the curvature of space tells matter how to move. The carrier particle of the gravitational force is the graviton.

What is electromagnetism?

Electromagnetism is the force that causes like-charged particles to repel and oppositely-charged particles to attract each other. The carrier particle of the electromagnetic force is the photon. Photons of different energies span the electromagnetic spectrum of x rays, visible light, radio waves, and so forth. Residual electromagnetic force allows atoms to bond and form molecules.

What is the strong nuclear force?

The strong force acts between quarks to form hadrons. The nucleus of an atom is hold together on account of residual strong force, i.e. by quarks of neighbouring neutrons and protons interacting with each other. Quarks have an electromagnetic charge and another property that is called colour charge, they come in three different colour charges. The carrier particles of the strong nuclear force are called gluons. In contrast to photons, gluons have a colour charge, while composite particles like hadrons have no colour charge.

What is the weak nuclear force?

Weak interactions are responsible for the decay of massive quarks and leptons into lighter quarks and leptons. It is the primary reason why matter is mainly composed of the stable lighter particles, namely up/down quarks and electrons. Radioactivity is due to the weak nuclear force. The carrier particles of the weak force are the W+, W-, and the Z bosons.

How are carrier particles different from other particles?

The photon, gluon, and the graviton carrier particles are thought to be massless and having no electrical charge. Only the W and Z particles, mediators of the weak nuclear force, are massive, and the W+ and W- particles carry charge. Force carrier particles can only be absorbed or produced by a matter particle which is affected by that particular force. These particles allow us to explain interactions between matter.

How old is the universe?

Today's most widely accepted cosmology, the Big Bang theory, states that the universe is limited in space and time. The current estimate for the age of the universe is 13.7 billion years. This figure was computed from the cosmic microwave background (CMB) radiation data that the Wilkinson Microwave Anisotropy Probe (WMAP) captured in 2002.

What came before the Big Bang?

The Big Bang model is singular at the time of the Big Bang. This means that one cannot even define time, since spacetime is singular. In some models like the oscillating universe, suggested by Stephen Hawking, the expanding universe is just one of many phases of expansion and contraction. Other models postulate that our universe is one bubble in a spacetime foam containing a multitude of universes. The "multiverse" model of Linde proposes that multiple universes recursively spawn each other, like in a growing fractal. However, until now there is no observational data confirming either theory. It is indeed questionable, whether we will ever be able to gain empirical evidence speaking in favour of these theories, because nothing outside our own universe can be observed directly. As yet the question cannot be answered by science.

How big is the universe?

The universe is constantly expanding in all directions, therefore its size cannot be stated. Scientists think it contains approximately 100 billion galaxies with each galaxy containing between 100 and 200 billion star systems. Our own galaxy, the Milky Way, is average when compared with other galaxies. It is a disk-shaped spiral galaxy of about 100,000 light-years in diameter.

What is the universe expanding into?

This question is based on the popular misconception that the universe is some curved object embedded into a higher dimensional space, and that the universe is expanding into this space. There is nothing whatsoever that we have measured or can measure that will show us anything about this larger space. Everything that we measure is within the universe, and so we see neither edge nor boundary nor centre of expansion. Thus the universe is not expanding into anything that we can see or measure.

Why is the sky dark at night?

If the universe were infinitely old, and infinite in extent, and stars could shine forever, then every direction you looked would eventually end on the surface of a star, and the whole sky would be as bright as the surface of the Sun. This is known as Olbers's paradox, named after Heinrich Wilhelm Olbers [1757-1840] who wrote about it in 1823-1826. Absorption by interstellar dust does not circumvent this paradox, since dust reradiates whatever radiation it absorbs within a few minutes, which is much less than the age of the universe. However, the universe is not infinitely old, and the expansion of the universe reduces the accumulated energy radiated by distant stars. Either one of these effects acting alone would solve Olbers's paradox, but they both act at once.

If the universe is only 13.7 billion years old, how can we see objects that are 30 billion light-years away?

This question is essentially answered by Special Relativity. When talking about the distance of a moving object, we mean the spatial separation now, with the positions of us and the object specified at the current time. In an expanding universe, this distance is now larger than the speed of light times the light travel time due to the increase of separations between objects, as the universe expands. It does not mean that any object in the universe travels faster than light.