Evolution of the Earth 9: Spaceship Earth - Physics from Newton to Einstein

Our picture of the universe and the solar system has changed dramatically in the last 500 years. At that time, most people thought that the Earth was a disk and was located in the center of the universe and that the stars were tiny points of light on the dome of the sky.

But today we know that the Earth is a planet orbiting the Sun (Fig. 1). Our Sun is one of over 250 billion stars in our home galaxy, the Milky Way. From Earth, more than 50 billion galaxies can be observed with current technology. Since 2016, research has assumed that there are about one trillion galaxies in the observable universe.

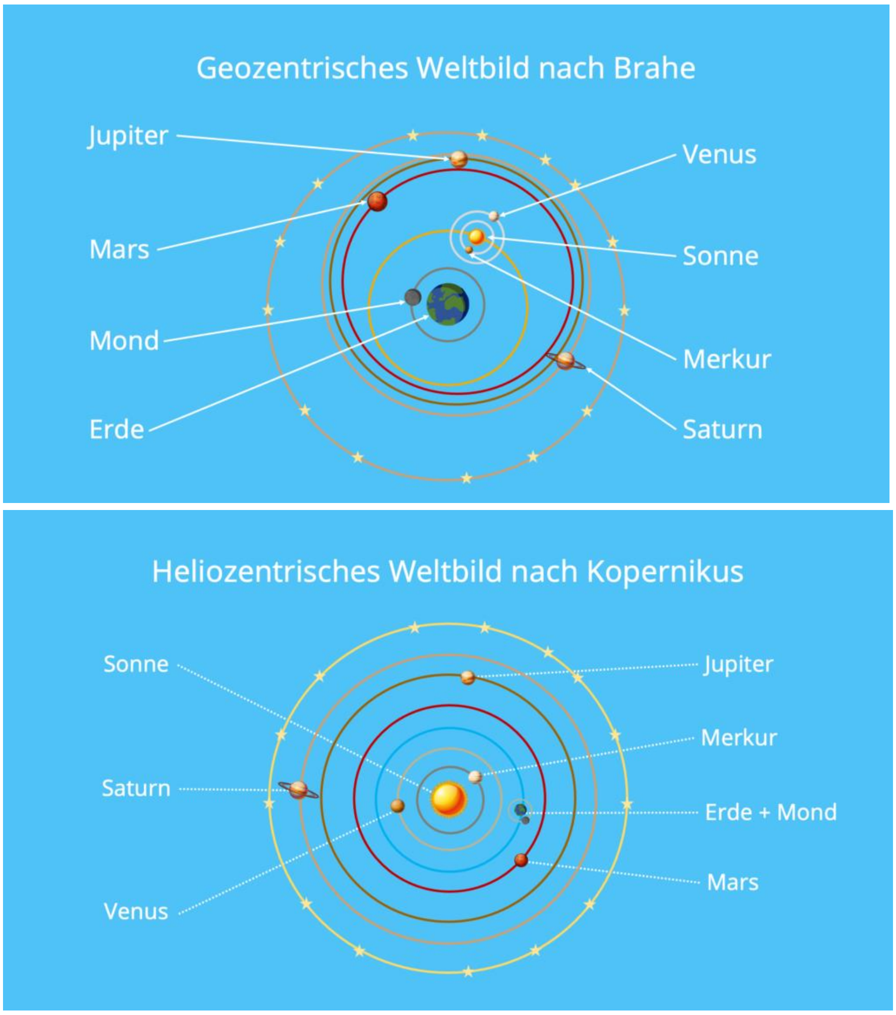


Fig. 1: Geocentric and heliocentric view of the world

But before we explore the origins of the universe, matter and our solar system, it is helpful to learn some physical laws that apply throughout the universe. We will go over some principles of physics from Newton to Einstein.

From Copernikus to Kepler

All motions, whether in atoms or in galaxies, are governed by a few physical laws. The exploration of the universe began already in the 16th century. In 1543 Copernicus proved that the sun and not the earth is in the center of our world and that the earth is only one of several planets orbiting around the sun (See Fig. 1). This Copernican turn accelerated the discovery of these laws and Galileo derived some of them from his experiments. In 1611, using one of the first telescopes, Galileo discovered that the stars, which have an almost infinite number, are not scattered on a large dome above our heads. He also confirmed that Jupiter has its own moons and used his telescope to show that Earth's moon is littered with craters and is not a perfect celestial sphere. Finally, he discovered that Venus, like the Moon, has its phases and showed that Venus moves in an orbit around the Sun that corresponds to our own orbit. Most importantly, he confirmed Copernicus' idea that the Earth is only one of several planets orbiting the Sun.

In the early 17th century, astronomer Johannes Kepler had deduced the laws by which planets move around the Sun. They are known as Kepler's laws.

The **first Kepler's law** states that the planets move on elliptical orbits. At a common focal point is the sun (Fig. 2).

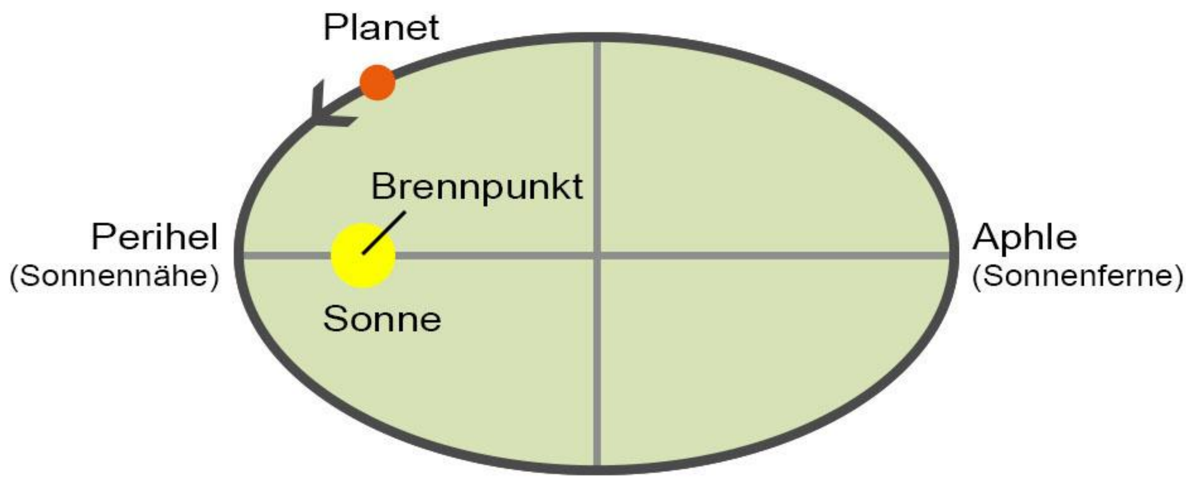


Fig. 2: The first Kepler's law

From this law follows that during the movement of planets around the sun the distance planet-sun changes constantly. For example, for the Earth the smallest distance from the Sun is 147.1 million kilometers (perihelion, beginning of January) and the largest distance is 152.1 million kilometers (aphelion, beginning of July). The mean distance of the Earth from the Sun has a value of 149.6 million kilometers. This distance is called astronomical unit (abbreviation: 1 AU).

Kepler’s second law states that a planet moves in its ellipse so that the line between it and the Sun placed at a focus sweeps out equal areas in equal times. (Fig. 3).

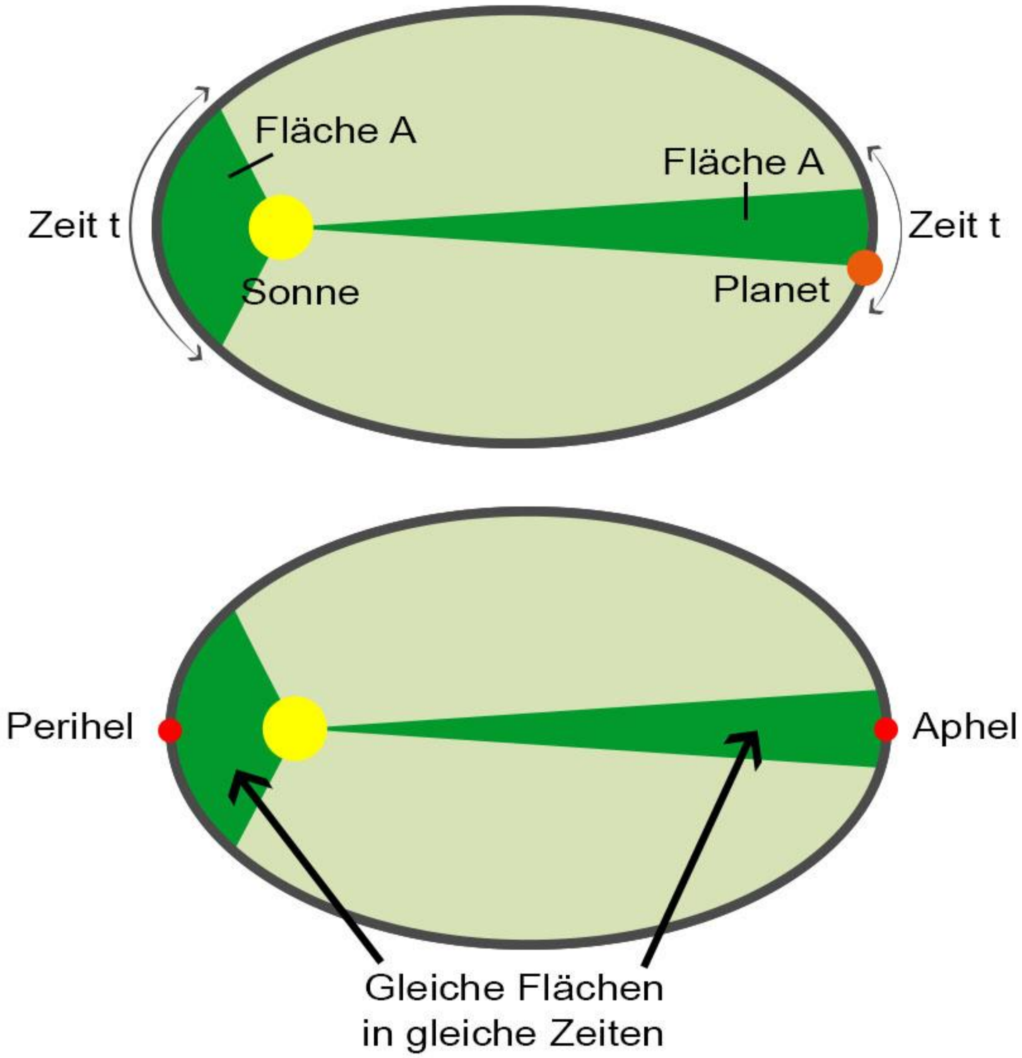


Fig. 3: The second Kepler's law

From this law follows that the planets move on their orbit with different speed. Near the sun they are faster than far from the sun. For the earth these velocities amount to 29.3 km/s in sun distance and 30.3 km/s in sun proximity.

The **third Kepler's law** describes the relationship between the size of the orbit and the time for one orbit around the sun. It reads: The squares of the orbital periods of the planets are directly proportional to the cubes of the semi-major axes of their orbits (fig. 4).

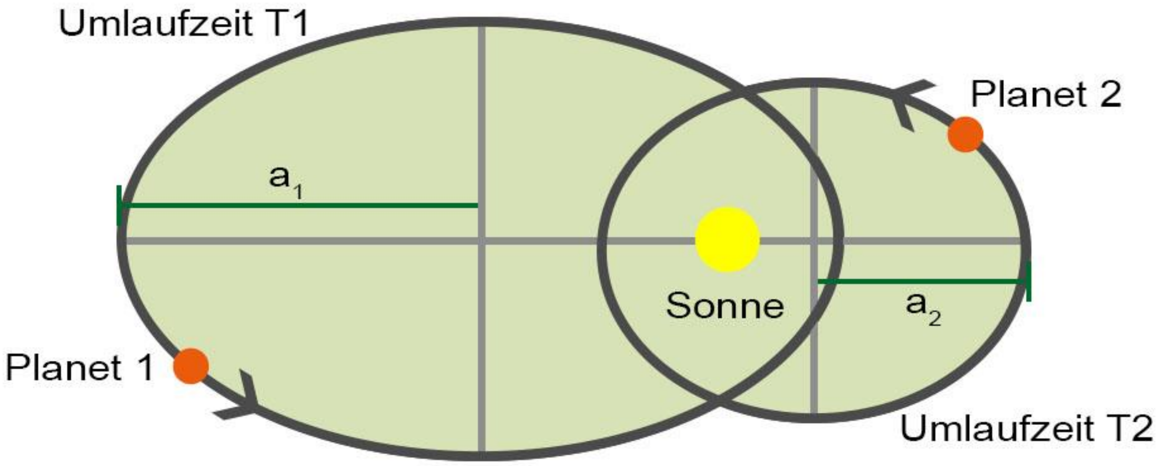


Fig. 4: The thirs Kepler's law

With the help of this law, the true dimensions of the planetary system can be derived from the observable orbital periods of the planets around the Sun. In particular, it follows from this law that the orbital velocity of planets decreases with increasing distance from the Sun. For example, Mercury, as the closest planet to the Sun, moves faster around the Sun than the Earth. The Earth, in turn, moves faster around the Sun than the planets Saturn or Jupiter, which are farer from the Sun.

Kepler's laws apply to the planets in the solar system to a good approximation. The deviations in the positions in the sky are mostly smaller than one angular minute. They are called orbital perturbations and are mainly due to the fact that the planets are not only attracted by the Sun, but also attract each other.

Kepler's three laws of planetary motion for the first time put human insight into the nature of the universe on a firm scientific footing. No longer did the planets wander across the sky at the whims of the gods, instead they followed mathematically defined orbits that could be calculated by simple laws. They remain of fundamental importance in astronomy to this day.

Newton

Despite his progress, Kepler did not know what force forced the planets into their orbits. This explanation should be found only 50 years later.

It was Isaac Newton who, from all the partial descriptions of Copernicus, Galileo and Kepler, formulated a simple system of equations describing both motion and gravity. Newton showed that the same physical laws that are valid on Earth are also valid in the cosmos. Therefore, we can learn about the universe by studying the laws of physics here on Earth.

Newton's most famous work is the "Philosophiae Naturalis Principia Mathematica" (Eng: The Mathematical Foundations of Natural Philosophy) of 1687. In this work, Newton combined Galileo's research on acceleration and Kepler's on planetary motion into a unified theory of gravity and laid the foundation stones of classical mechanics by formulating the three fundamental laws of motion. We know terms like velocity, acceleration, force etc.. But what do they mean in the physical sense?

Velocity is a movement with a certain speed in a certain direction, e.g. "100 km/h northward" (Fig. 5).

Formel:	**Kurzform:**
$\text{Geschwindigkeit} = \dfrac{\text{Strecke}}{\text{Zeit}}$	$v = \dfrac{s}{t}$
$\text{Strecke} = \text{Zeit} * \text{Geschwindigkeit}$	$s = t * v$
$\text{Zeit} = \dfrac{\text{Strecke}}{\text{Geschwindigkeit}}$	$t = \dfrac{s}{v}$

Fig. 5: Velocity

Acceleration is a change in velocity (Fig. 6), that is, a change in magnitude or direction. A reduction of velocity, e.g. by braking, is also a (negative) acceleration.

Beschleunigung (skalar)

	Einheit	Anmerkung
$a = \dfrac{\Delta v}{\Delta t}$	1 m/s^2	Beschleunigung
$v, \Delta v$	1 m/s	Geschwindigkeit, Geschwindigkeits-Intervall
$t, \Delta t$	1 s	Zeit, Zeitintervall

Die Beschleunigung ist ein Quotient. Zähler: Änderung der Geschwindigkeit, Nenner: Zeit während der Änderung

Fig. 6: Accleration

One of the most important types of acceleration is that caused by gravity (gravitation). All objects, regardless of their mass, experience the same gravitational acceleration and abbreviated as "g". However, gravity acceleration is affected by air resistance.

That is why a feather glides easily to the ground, while a stone plops down. In an airless space (vacuum), however, both fall at the same rate (Fig. 7). On Earth, gravity causes falling objects to speed up 9.8m per second, i.e. 9.8m per second squared (g= 9.8m/s2).

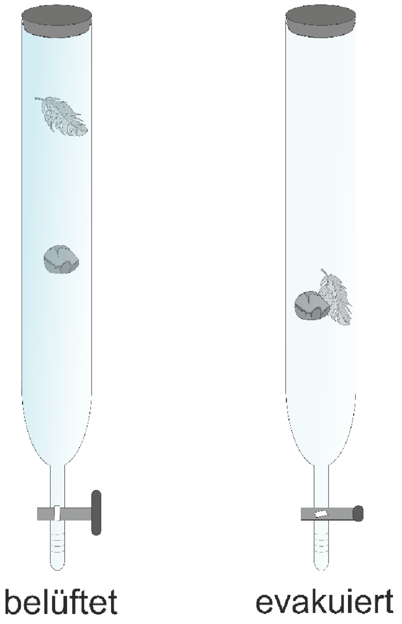


Fig. 7: freier Fall

Mass is a measure of the amount of matter in a body. In contrast, **weight** is a measure of the gravitational attraction acting on a body (Fig. 8). The mass of an object is always the same, no matter where the mass is located. However, weight changes with the strength of gravity or other forces acting on the object.

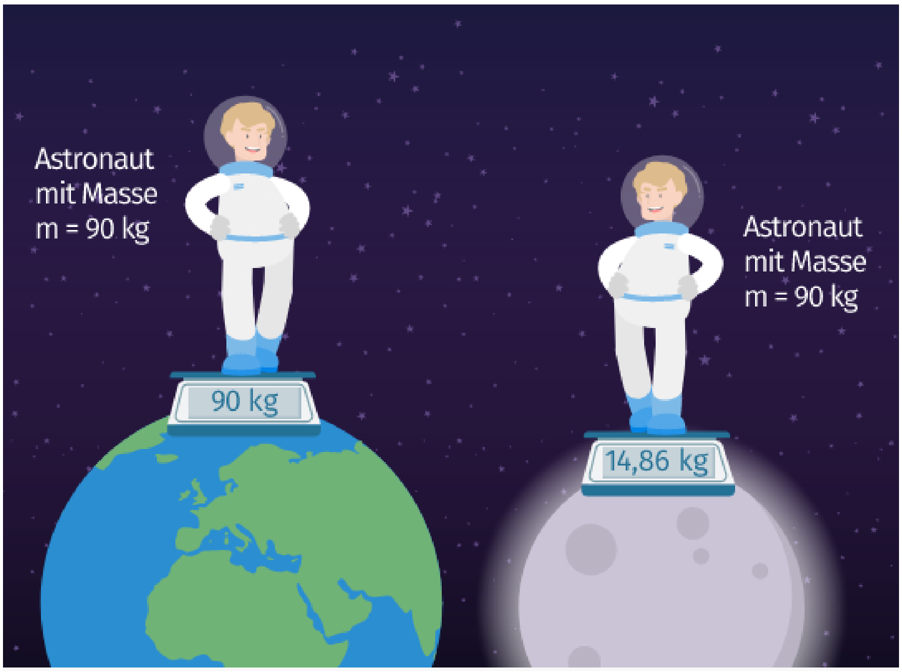


Fig. 8: Mass and weight

An object becomes weightless in free fall, but its mass remains unchanged (Fig. 7). The fall of a stone from a height of 20 m or the jump of a person from a 10 m tower can be considered as free fall, because in these cases the air resistance can be neglected. For a skydiver floating on a parachute, the laws of free fall are not applicable because in this case air resistance cannot be neglected.

Velocity and acceleration describe how a single object moves, but many interesting phenomena in the universe, are based on the interaction between objects. Therefore, we need two more terms to accurately describe these interactions: Momentum and Force.

Momentum is mass * velocity (p = mv). The momentum of a physical object is larger the faster it moves and the more massive it is (Fig. 9).

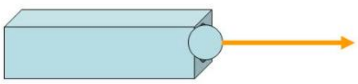
Definition des Impulses

	Einheit	
$\vec{p} = m \cdot \vec{v}$	1 kg m/s	Der Impuls ist ein Vektor: Produkt aus Masse und Geschwindigkeit

Fig. 9: Momentum

The only way to change the momentum of an object is to apply a **force** to it that accelerates it (Fig. 10). Consequently, force = mass * acceleration (F= ma).

Änderung des Impulses: Die Kraft



	Einheit	
$\vec{p} = m \cdot \vec{v}$	1 kg m/s	Impuls
$\frac{\Delta \vec{p}}{\Delta t} = m \cdot \frac{\Delta \vec{v}}{\Delta t} = \vec{F}$	1 kg m/s^2	Der Quotient aus Impulsänderung und Zeit ist die Kraft

In dem Kasten wirkt eine Kraft beschleunigend auf die Masse

Fig. 10: Force

Some force is always acting, for example the mentioned gravity. The resulting force acting on an object represents the combination of all forces (Fig. 11).

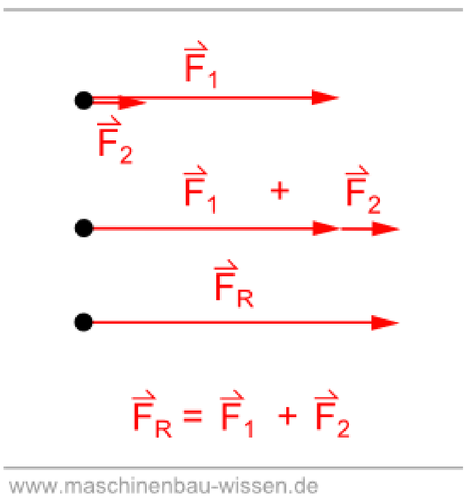


Fig. 11: Effect of resultant forces

When we travel at constant speed, there is no resultant force because the force generated by the motor to drive the wheels exactly balances the forces of air resistance and friction. A change in momentum of an object occurs only if the resultant force is not zero, that is, the object changes its velocity, provided its mass remains constant. A non-zero resultant force causes the object to accelerate. Using the same ideas, we can also understand many astronomical processes. For example, planets experience constant acceleration as they orbit the sun because the direction of motion in their orbit is constantly changing.

A body that rotates on its axis or moves along a curved path, as is the case with planets but also, for example, with a figure skater, has angular momentum. If a force, a so-called torque, acts on a rotating body, its angular momentum changes.

From these findings, Newton derived three laws of motion that explain not only our movements on Earth, but in the entire universe.

1st Newton's law: An object moves with constant speed if no resulting force acts on it.

2nd Newton's law: Force = mass * acceleration. In astronomy, Newton's second law explains why a large planet like Jupiter has a greater influence on asteroids and comets than a small planet like Earth. Jupiter exerts a stronger gravitational force on passing objects than Earth, so Jupiter accelerates asteroids more.

3rd Newton's law: For every force, there is always an equal and opposite force. This law says, for example, that objects always attract each other because of gravity. So our body exerts a large attractive force on the earth as the earth exerts on us, except that this force is in the opposite direction. Of course, "the same force" means a much higher acceleration for us because our mass is so small compared to the Earth. Therefore, when we jump from the chair, we fall on the earth and not the earth on us.

But why should any force have an equal and opposite opposing force? This reflects essential aspects of nature, which are called conservation laws. Bodies have **conservation of momentum**, rotating bodies have **conservation of angular momentum**.

Conservation of momentum means that the momentum of an object cannot change unless momentum is transferred to or from another object. If no force is acting, no momentum can be transferred, so an object maintains velocity and direction.

Conservation of angular momentum means that, for example, a planet's rotation around its orbit or its proper rotation cannot change unless it would transfer angular momentum to another object. The planets in our solar system do not exchange significant amounts of angular momentum with each other or with other objects, so their orbits and rotational speeds remain largely stable. The Earth does not need fuel or any kind of push to continue orbiting the Sun - it will continue moving as long as nothing gets out of the way and its angular momentum decreases. The Earth's orbital angular momentum is the product of its velocity and its distance from the Sun. Thus, the orbital velocity of the Earth increases the closer it is to the Sun.

Energy is also always conserved - it can neither be created nor destroyed. All objects have got any energy, which they possess now, by the exchange with other objects. Energy essentially occurs in three categories, as kinetic energy (also called kinetic energy), radiant energy, and potential energy. Potential energy, or stored energy, can be converted into kinetic or radiant energy at a later time.

Newton expressed the gravitational force mathematically in his **general law of gravitation** (Fig. 12). Here, every mass attracts every other mass by the gravitational force. The strength of the gravitational force that two objects exert on each other is directly proportional to the product of their masses. If you double the mass of one object, you double the gravitational force between the two objects. The strength of the gravitational force between two objects decreases with the square of the distance between their centers. If you double the distance between two objects, the gravitational force decreases by a factor of 4. Mathematically, this is expressed in the equation

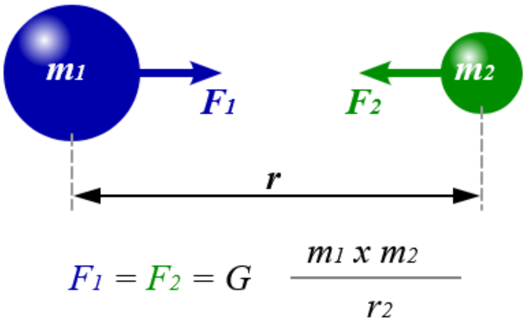


Abb. 12: general law of gravitation

M1 and M2 are the masses of the objects, r is the distance between their centers, and G stands for the gravitational constant.

Kepler's laws mentioned earlier are corollaries of the laws of motion and the general law of gravitation. Newton showed that any object orbiting another satisfies the first two of Kepler's laws. He showed that closed orbits on ellipses (which include circles) are not the only possible orbital shapes. There are also open orbits in the form of hyperbolas and parabolas. For example, some comets that enter the interior of a solar system move in this way. Newton also proved that two celestial bodies actually orbit their common center of gravity. The moon and the earth move their orbits around the common center of gravity, but since the earth is much more massive than the moon, the common center of gravity is about 1700 km below the earth's surface. The Newtonian version of Kepler's third law also makes it possible to calculate the masses of orbiting celestial bodies based on their orbital periods and distances.

The problem with the Mercury perihelion

For more than two centuries, Isaac Newton's laws had passed every conceivable test and seemed to represent a fundamental truth of the universe.

What finally convinced skeptics of the correctness of Newton's ideas, for example, was the orbit of a particularly bright comet calculated by Edmund Halley and his prediction that it would return after 76 years. When the comet - later called Halley's Comet - reappeared at the end of 1758, Newton's laws had finally been accepted as the correct description of the world and the bodies moving in it.

But toward the end of the 19th century, an ever-increasing number of astronomers and physicists realized that Newton's theories did not always provide the correct answers.

A small deviation from the expected behavior of the planet Mercury was an indication that the law of general gravitation was not as universally valid as had been thought.

Kepler's First Law states that the orbits of the planets are ellipses of a very definite shape and size. Observations showed, however, that although the shape and size remain the same with each orbit, the orbit of a planet changes from orbit to orbit.

The point of closest approach to the Sun is called perihelion. However, because of the gravitational attraction of the other planets, the location of the perihelion in space is in motion, performing a precession around the Sun. A precession is the change of direction of the axis of a rotating body (Fig. 13).

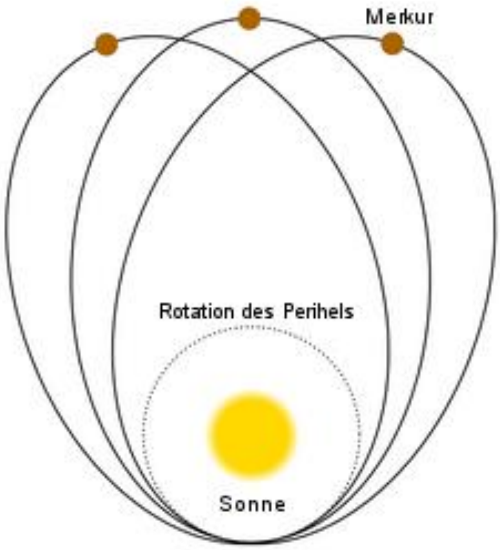


Fig. 13: Precession of the planet Mercury

Newton predicted this precession. However, more detailed studies showed that while the attraction of the other planets could account for most of the observed precession of the planet Mercury, there was a small, fixed portion of the precession that could not be explained - until Albert Einstein entered the scene.

Before we get into Einstein and his theories, however, we need to backtrack a bit, because Einstein's theories didn't come out of the blue. First, we'll introduce some other scientists who paved the way for Einstein's revolution through their research on electromagnetism and the speed of light.

James Clerk Maxwell

James Clerk Maxwell most significant finding was that electricity and magnetism are closely related. Both are manifestations of the same thing, which he called the electromagnetic field. Maxwell's theory of electromagnetic fields focuses on the space in the neighborhood of electric or magnetic bodies.

Magnets have a north and a south pole. When we bring two magnets with their north poles (or their south poles) together, a repulsive force occurs. But if we bring the south pole of one magnet together with the north pole of the other, the magnets attract and stick to each other. What happens if we scatter iron filings on a sheet of paper and hold a magnet under the paper? The filings arrange themselves in a series of curved lines called magnetic field lines that run from the north pole to the south pole (Fig. 14).

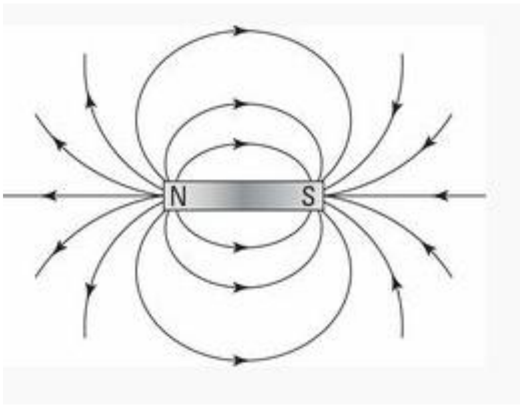


Fig. 14: Magnetic field lines

These lines show the electromagnetic force experienced by a body when it is affected by a field. The direction of the lines shows the direction in which the force acts, and the density of the lines reveals something about the strength of the force.

It turns out that electrically charged bodies also generate fields (Fig. 15). Let us imagine two steel balls, one with a negative electric charge, the other with a positive one. If we bring positively charged balls close to these two balls, we see that a field similar to magnetic field lines is created. Maxwell showed that they not only look alike, but under certain circumstances they are the same. A clever mathematical calculation showed that a moving magnet produces an electric field and that a moving electric charge produces a magnetic field.

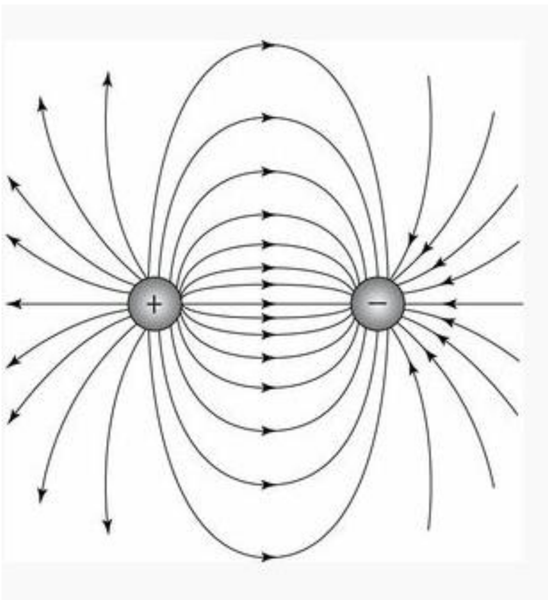


Fig. 15: Electric field lines

Perhaps the most remarkable thing about Maxwell's equations is their prediction that electric and magnetic forces propagate through wave-like oscillations at a fixed speed.

Maxwell's calculations showed that the speed of electromagnetic waves is 288,000 kilometers per second, which is almost exactly the same as the speed of light, which had been measured by French scientist Hippolyte Fizeau in 1849 to be 313,000 kilometers per second using a rotating mirror. Maxwell recognized the significance of this coincidence and concluded that light (including other radiations) is a form of electromagnetic radiation (Fig. 16). Maxwell's theoretical considerations were later confirmed by the German physicist Heinrich Hertz when he produced radio waves, which are another form of electromagnetic radiation.

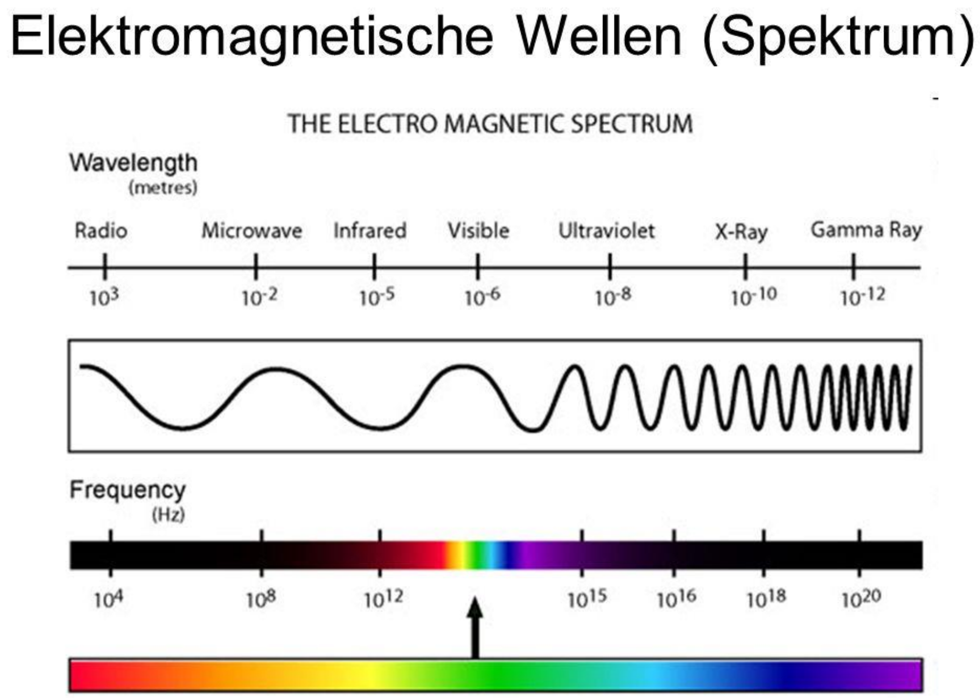


Fig. 16: Electromagnetic waves

His new insights into electromagnetism presented Maxwell with another problem: What was the carrier of all these waves? His idea was that there was a substance, which he called "light aether," which filled space, penetrated everything, and in which the electromagnetic waves propagated like sound in the air. This idea had been common since the time of Aristotle - the only problem was that it had never been possible to prove the existence of such an aether.

The abolition of the aether

Maxwell's notion that a mysterious substance called ether was necessary for the propagation of electromagnetic waves in space undoubtedly posed a problem for scientists. Then two U.S.-based scientists, Albert Abraham Michelson and Edward Williams Morley, devised an experiment by which they hoped to measure the motion of the aether - if it existed - at the Earth's surface.

The experiments were based on the idea that the Earth, orbiting the Sun, was moving relative to the aether and therefore some sort of "aether wind" should be detectable.

This wind, the scientists thought, should cause small changes in the speed of light that should be measurable by laboratory instruments. The problem was that the difference in the speed of light would be very small.

The duo set up an experiment in which a beam of light is split into two individual beams that propagate at right angles to each other (Fig. 17).

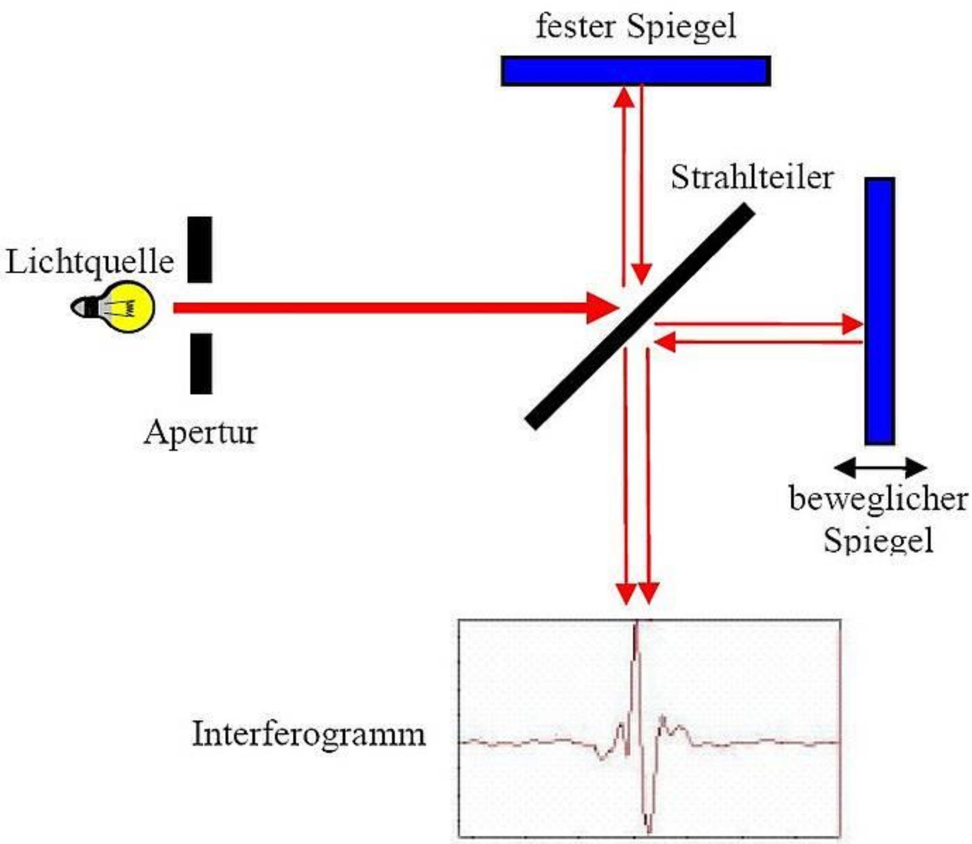


Fig. 17: Experiment of Michaelson and Morley

First, Michelson and Morley sent a beam of light through a semi-transparent mirror that was designed to reflect half of the light falling on it and transmit the other half. Because of the nature and angle of the mirror, half of the light continued to move straight ahead, while the other half was deflected at right angles. Each of the light beams was reflected by other mirrors and finally arrived at a light detector, a ground glass screen. In the light detector, the two light beams create an interference pattern, a series of light and dark fringes that are created when the two light waves are recombined. This experimental setup was built on a large block of marble floating on a pool of mercury to suppress any vibrations that might simulate the effect they were looking for.

Michelson and Morley hoped that the interference pattern caused by the two beams of light would show that the two beams traveled their paths with little difference in speed. But their experiments showed no difference at all at different orientations or at different times of the day or year - a clear indication that the notion of an ether was wrong. In fact, the experiment has been repeated many times by many scientists since Michelson and Morley's experiments, and the result has always been the same. So the speed of light, usually abbreviated by the letter c, is independent of the reference frame and is always about 300,000 meters per second in empty space.

A few years had to pass before the real consequences of these experiments became apparent. Michelson and Morley's experiment suggested that there was a universal constant speed of light, and this put Einstein on the track to his most famous equation describing the subtle interaction between mass and energy, which is of great importance in the early universe.

Special Theory of Relativity

Albert Einstein took the constancy of the speed of light as a reason to question the existence of an absolute and generally valid time.

If Einstein's relativity theories are also jokingly (and wrongly) generalized to "everything is relative": Einstein's initial question about relativity and absoluteness is much more limited. It deals only with a very special class of situations and observers.

Let us imagine that we are in a railroad train moving at a constant speed of 100 km/h on a straight railroad track. While we are sitting in our seats, a conductor is walking through the train from front to back at a constant speed of five kilometers per hour.

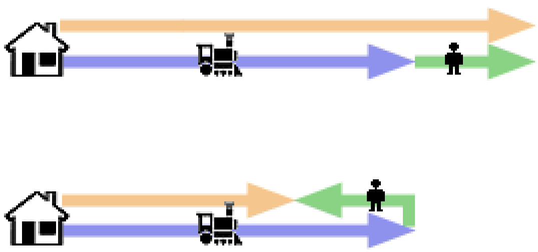


Fig. 18: Galilean relativity

From our point of view - or in our frame of reference, as physicists say - the conductor is moving away from us at five kilometers per hour. To keep up with him, we would also have to run after him at five kilometers per hour.

But for a friend on the platform outside the train, it's much harder to keep up with the conductor. He has to move at a different speed - 100 kilometers per hour minus 5 kilometers per hour, or 95 kilometers per hour - to keep up with the conductor.

So what is the conductor's speed? Is it 5 kilometers per hour or 95? Well, that depends on our frame of reference.

In other words, there is no way for us on the train to determine whether the conductor is moving at 5 kilometers per hour or 95. There is no method to distinguish between rest and uniform motion. Scientists call this experience Galilean relativity.

Einstein realized that Galilean Relativity encounters a difficulty when considering electromagnetic phenomena (such as light).

In his attempt to reconcile Galilean relativity with Maxwell's laws of electromagnetism, Einstein worked on the basis of two postulates:

1. the laws of physics are the same in all non-accelerated reference frames.

2. the speed of light is the same in all non-accelerated reference frames.

To get a sense of how the absolute magnitude of the speed of light causes time to slow down (dilation), let's imagine that we are on a train in motion - again (Fig. 19)! We let a laser beam pass back and forth between two mirrors; one should be on the floor, the other on the ceiling of the carriage.

Let's imagine that we can measure the time interval it takes for the light to travel from the floor to the ceiling and back again.

Now let's imagine that a friend standing on the platform can also observe how the light travels back and forth. He sees it running diagonally up and then diagonally down again. From his point of view, the light covers a further distance than from our own.

If the laws of physics - and especially Maxwell's equations - are the same in all uniformly moving reference frames, the speed of light observed from the train should be the same as that observed from the platform.

The end of the story is this: When our friend on the platform measures on his wristwatch the time taken for the light to travel back and forth, he will find that it is longer than one second. From his point of view, time passes slower on the train than for him on the platform.

The speed of light is the same for all constantly moving observers. How is this possible? Einstein's answer was that although the speed of light is constant, time does not pass uniformly. Einstein's Special Theory of Relativity stated that time is stretched for an observer in motion and that space contracts for him.

In June 1905, Einstein published the results of his solution in the journal Annalen der Physik under the title "On the Electrodynamics of Moving Bodies."

The results of Einstein's calculations indeed showed that they solved the problem posed in the Michelson-Morley experiments.

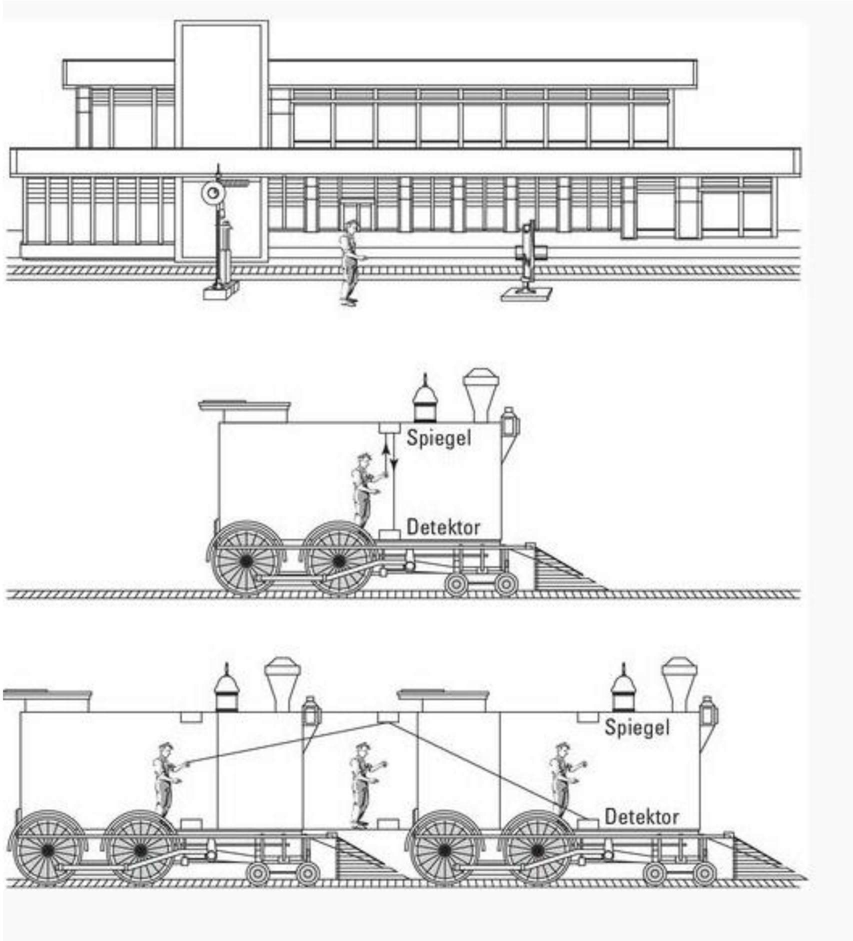


Fig. 19: (Top) You see how the light beam runs up, is reflected and runs down again. (Bottom) Your friend sees the light beam travel up along one diagonal, and after reflection, travel down along another diagonal.

This observation is one of the most important in special relativity: In a moving reference frame, time passes more slowly. Because the speed of light, which is a distance divided by a time, must remain constant, Einstein was also able to show that in a moving frame of reference, space contracts.

Suddenly, then, space and time were no longer the fixed stage on which the events of the universe took place, as had once been assumed by Newton and others. This changeability in time and space may seem strange to us and so not at all fit to the experiences of the daily life. But this is because we never move close to the speed of light. But scientific experiments have shown again and again that this change of space and time really occurs.

Shortly after Einstein published his Special Theory of Relativity in June 1905, he put into print another short paper entitled "Does the Inertia of a Body Depend on Its Energy Content?" In this paper, he used the principles of special relativity to show that the mass of an atom decreases when it emits light or other electromagnetic radiation, such as a laser or a radioactive source emitting X-rays. In short, Einstein's work showed that the mass of a body is a measure of how much energy is in it. This means nothing other than that matter and energy are interchangeable! And what does this mean? E= mc2

Energy is a form of mass, and mass is a form of energy. Because the factor between them is such a large number (the square of the speed of light), even the smallest piece of matter has the potential to release an enormous amount of energy.

The mass of an object increases as its velocity increases. As the speed of an object approaches closer and closer to the speed of light, its mass increases more and more, to the point where it is no longer possible to accelerate it any further. This is also the reason why no massive object can travel faster than light.

General relativity

Einstein knew the importance of his work on special relativity, but he recognized from the beginning that his theory was limited to a particular kind of motion - motion without acceleration. A decade later, in 1916, he finally developed the general theory of relativity. This describes the interaction between matter on the one hand and space and time on the other. It interprets gravitation as a geometrical property of the curved four-dimensional space-time. In order to understand this, let us engage in a thought experiment, which Einstein himself carried out.

What actually happens in an elevator if you cut the cables and everything - the elevator together with the passengers - falls down freely (fig. 20)?

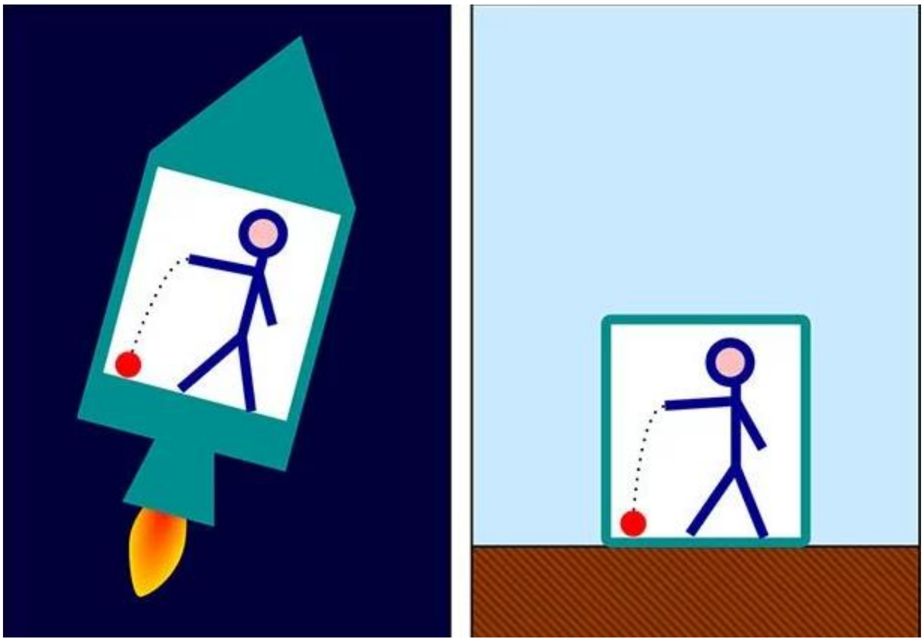


Fig. 20: What would actually happen in an elevator if the cables were cut and everything - the elevator and its occupants - fell freely downwards?

The falling people in the elevator would not be able to tell whether they are being pulled down by gravity or accelerated in some other way at the same rate. Einstein's idea: no physicist could decide by any experiment, no matter how sophisticated, whether he was in a gravitational field of a body or in an accelerated frame of reference, precisely the elevator.

Einstein concluded that acceleration and gravity are interchangeable. This "equivalence principle" became the linchpin of general relativity.

Einstein realized that the fact that gravity and acceleration are interchangeable has great significance for light.

To understand this, let us imagine that we are sitting in a spaceship that is flying through space at an accelerated speed (Fig. 21). On the side of the spaceship there is a small hole through which a beam of light enters and causes a light spot on the opposite cabin wall.

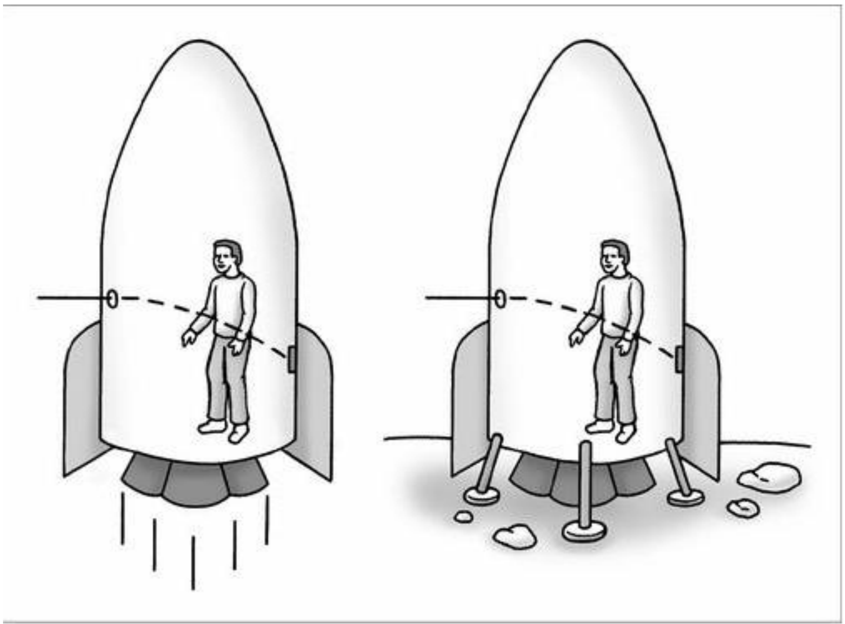


Fig. 21: In an accelerated spaceship, a beam of light appears to be curved to the scientist.

As the spacecraft is accelerated, one finds that the light spot strikes the cabin wall lower than if the ship were stationary - as if the light were bent in an arc toward the ground. This may all still be quite simple to understand. But we remember that gravity and acceleration have the same effect. Therefore, gravity should have the same effect on the beam of light entering the spacecraft - it should bend a little.

In general relativity, it can be shown that it is not gravity that causes the curvature of a light beam. Instead, spacetime - a mathematical construction that unifies space and time, and in which space is usually three-dimensional and time assumes the role of a fourth dimension - is itself curved, and light simply takes the shortest path from its source to its destination.

Perhaps the best way to imagine spacetime is to imagine a rubber skin stretched horizontally (Fig. 22).

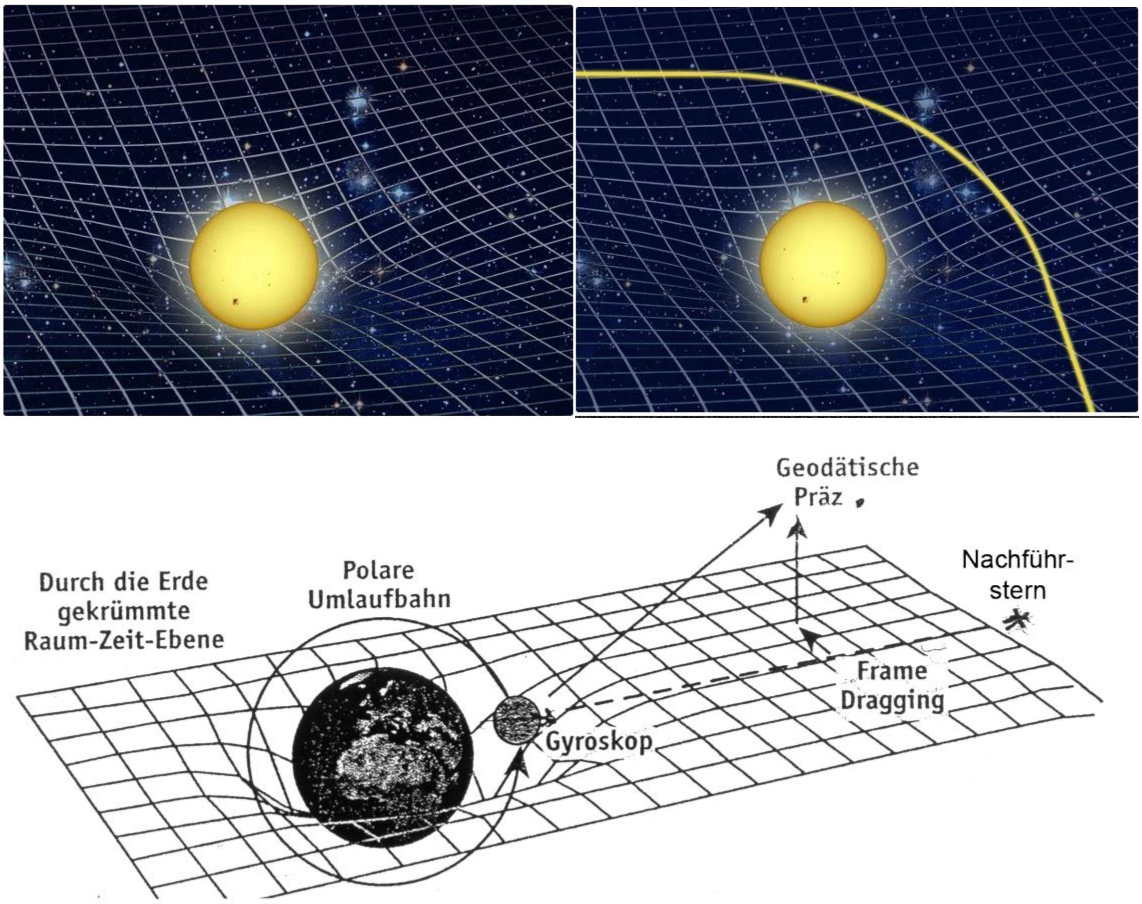


Fig. 22: Spacetime represented in two dimensions. The mass curves the space-time. The light simply takes the shortest path from the source to its destination.

Now let us imagine that we put a cannonball in the center of the rubber surface. What happens now? The cannonball depresses the rubber surface and causes a dent. If we now let a marble roll over the rubber surface, it will roll in the direction of the cannonball. If we try to roll the marble past the cannonball, it will travel a curved path.

Einstein's General Theory of Relativity shows that what we perceive as gravity - the fall of an apple to the earth, the force that keeps the moon in its orbit around the earth, and the planets around the sun - is not a force at all in the real sense. The mass that curves space-time makes us believe that a force is at work.

Calculating the curvature of space-time is one thing, proving its reality is another. Even on large scales, the curvature of spacetime is tremendously small. Einstein himself recognized the problem when he said that the curvature was "extremely small for the gravitational fields we are dealing with in practice."

To test the theory of the curvature of spacetime, we need to examine light passing close to a massive celestial body, such as our Sun, because then we can determine whether the body's gravity is bending a beam of light. Normally, the sun is so bright that other light is drowned in its abundance. Fortunately, every now and then nature provides us with an excellent sunshade - a total solar eclipse (Fig. 23).

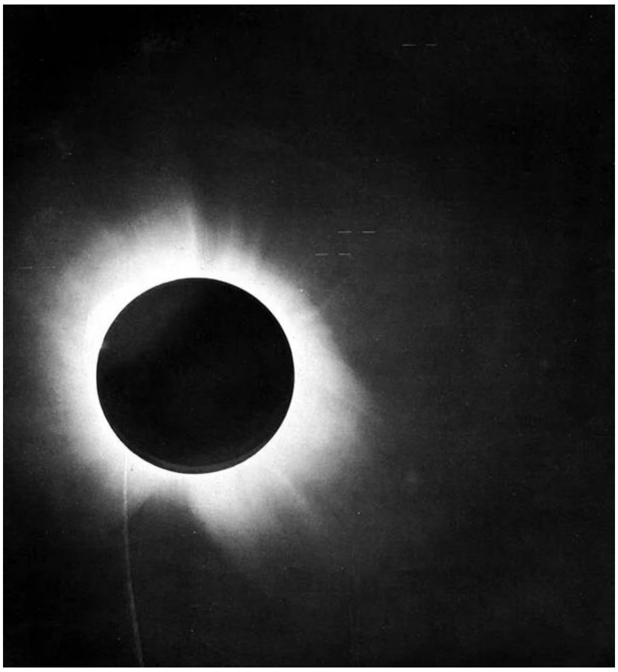


Fig. 23: Solar eclipse

For this we look at stars near the edge of the sun. If Einstein is right, the location of a star near the edge of the sun should be slightly shifted because the light coming from the star to us is bent by gravitational attraction.

Einstein calculated that starlight passing exactly at the edge of the Sun is bent by the tiny fraction of a degree, which is about the size of a penny at a distance of 3 kilometers (Fig. 24).

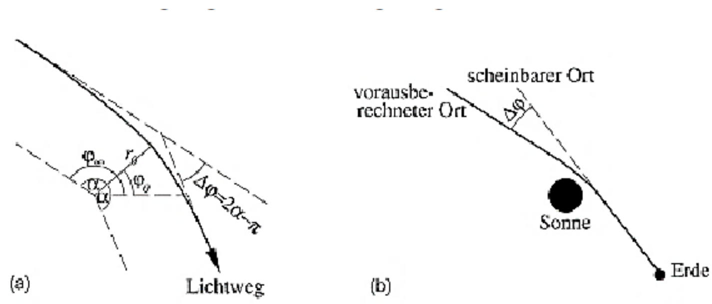


Abb. 2-3
Lichtablenkung am Sonnenrand[27]

Fig. 24: Light deflection at the solar limb

By comparing the location of the star on the day of the eclipse with a location recorded in a star atlas, the curvature of the star's light can be detected.

During the total solar eclipse of May 29, 1919, astronomer Arthur Eddington visited Principe Island on the west coast of Africa and took a picture of the stars in the Hyades star cluster, which were near the edge of the sun at the time. Although clouds made observation nearly impossible, it cleared enough to obtain a photographic image (Fig. 23). Eddington was able to detect stars and found that the displacement of the stars was consistent with Einstein's calculations.

Let us return to Mercury's periphyton.

The fact that Mercury's orbit was constantly changing put astronomers in a bind for explanations. As solutions dust in the proximity of the sun, a hypothetical planet still within the Mercury orbit or the flattening of the sun circulated. But none of these effects could explain why Mercury's orbit shifts by 43 arc seconds or just over 10,000 kilometers per century - this was only achieved when Albert Einstein took on the problem. With the general theory of relativity, the deviation of Mercury's orbit, i.e. these 43 arc seconds, could be calculated exactly. For Albert Einstein, the Mercury orbit was a very important achievement in the development of his theory.

In our everyday life the differences between the Newtonian and the Einsteinian set of rules are mostly not noticeable. It is only when large masses and extreme precision are involved that the relativistic effects must also be taken into account.

As scientists explored the universe more and more thoroughly with large telescopes, they discovered that the light from distant stars was also a very important tool to study the expansion of the universe. Indeed - although the universe is huge, it continues to expand. The expansion of the universe tells us a lot about its origin and its future - and we'll deal with that in the next post.

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