The Speed of Light

{Abstract: *In this segment of the "How Fast Is It" video book we cover the speed of light. We start with the slow-moving snail and work up through people, animals, birds, cars, aircraft and spaceships. Along the way we graph speeds on a space-time diagram. Following the history of land speed records, we cover the speed of sound and include its nature as a longitudinal wave and its speed in dry air and the sound barrier. We then cover the Galilean transformations for converting speeds from one reference frame to another. We increase the velocities to the point where we see light traveling at different speeds as far as the Galilean transformations are concerned. We then show how Galileo tried and failed to measure the speed of light; Romer's use of Jupiter's moon Io; and then we show how Antonio Louis Fizeau did measure the speed of light. We'll also cover Maxwell's speed of light calculations; We then cover wave interference and the Michelson Interferometer. And using the interferometer, we cover the Michelson-Morley experiment that showed that the speed of light was a constant. We finish with a look at the two main modern ways for measuring the speed of light.* **}**

Introduction

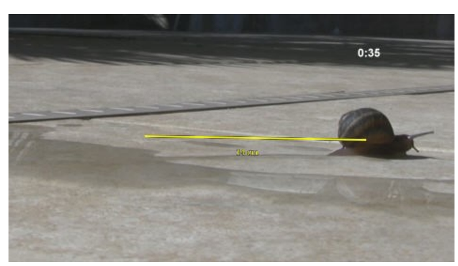
Hello and welcome again to my backyard where we'll begin our video book "How fast is-it".

We started here in the first video book, "How far away is it" where we went from my backyard to the furthest reaches of the visible universe. We started here again when we did, "How small is it" which took us down to the smallest things that exist.

In this video book, we'll start with the things in our back yard; snails, people, birds. And move on to faster and faster things, including the speed of light. And along the way, we'll cover how we measured things like: the speed of sound; the speed of light. So, we'll get going. We'll start with the lowly snail.

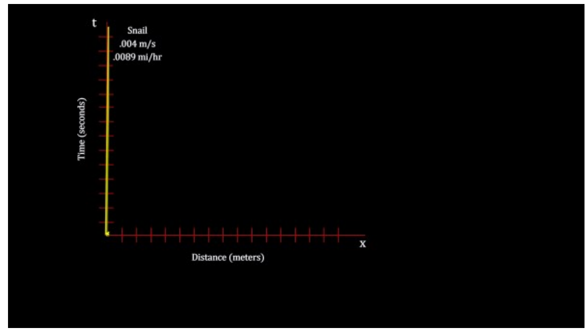
Snails **[Music**: @00:00 Giachino Rossini - William Tell Overture**]**

Here we see a snail making good time across the tile. We can measure the distance traveled and the amount of time it took. We define speed as the distance divided by time. Here we have 14 cm (5.5 inches) traveled in 35 seconds. [That's 0.4 cm/s (or 0.157 in/s)]



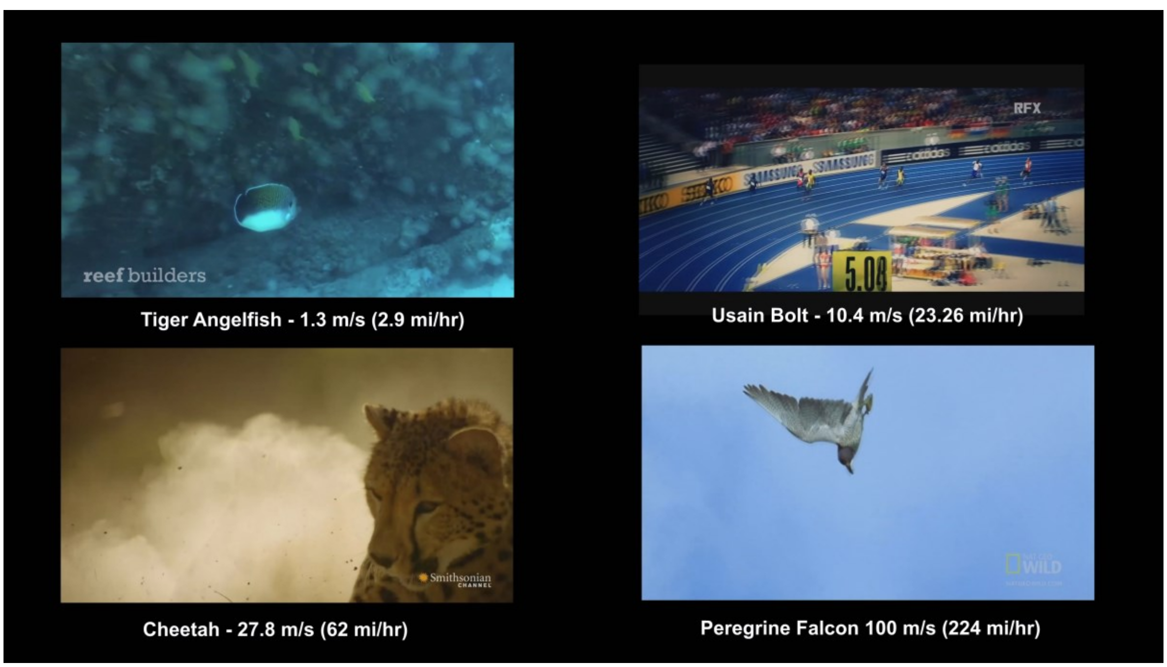
*[**Music**: Beethoven – Symphony No 7 Allegretto]*

If we plot this on the time vs distance graph with time in seconds for the vertical axis and distance in meters for the horizontal axis, we see that 'slow' is a very steep line. Standing still would be a line going straight up.



Other animals

Here's a Wild Tiger Angle fish. They have been seen to move at around 1.3 m/s. That's 2.9 mi/hr. Of course, people can move a lot faster than this. The fastest man alive is the Jamaican Usain Bolt who ran the 200 m in 19.19 s or 10.4 m/s. [That's just over 23 mi/hr.] But that's slow compared to Cheetahs. They're the fastest mammal topping 27.8 m/s – [that's 100 km/hr or 62 mi/hr.] But the Peregrine Falcon puts that to shame. They are the fasted animal on the planet soaring up to 389 km/hr. That's 25,000 times faster than the snail.



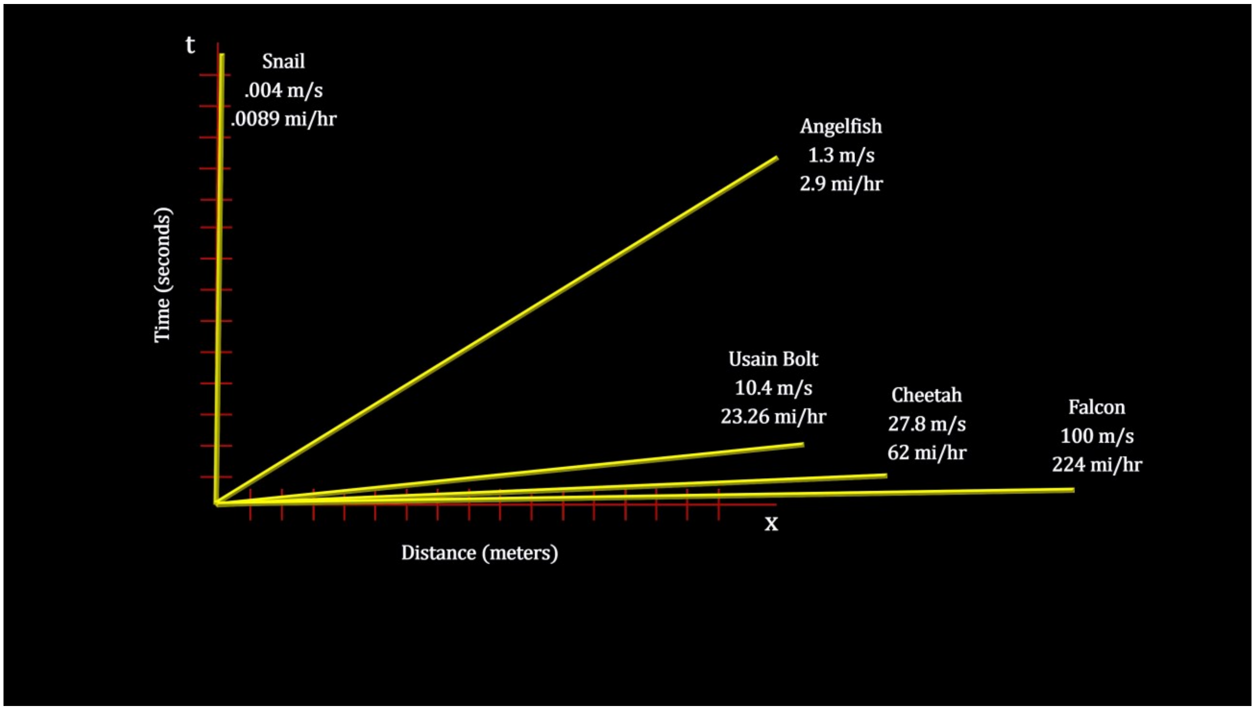
Tiger Angelfish - 1.3 m/s (2.9 mi/hr)

Usain Bolt - 10.4 m/s (23.26 mi/hr)

Cheetah - 27.8 m/s (62 mi/hr)

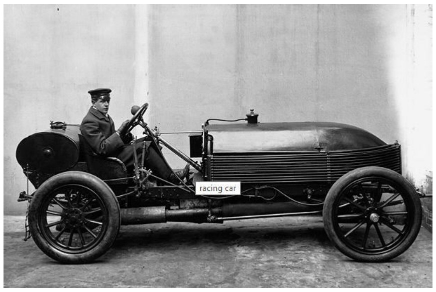
Peregrine Falcon 100 m/s (224 mi/hr)

Graphing these speeds against the snail's almost vertical line, shows how horizontal the lines can get at faster velocities.



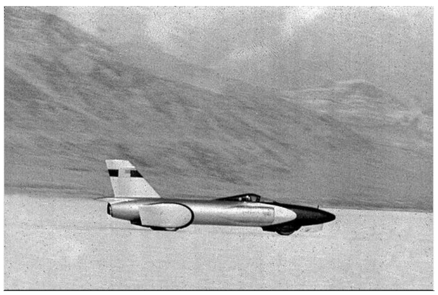
Land speed records

Of course, we have cars that can travel faster than any of these animals.



Arthur MacDonald was one of the first to capture the land speed record at Daytona Beach in a Napier back in 1905. It set the record with 168.4 km/hr. [That's 104.6 mi/hr.]

Malcolm Campbell, took the record in 1935 in his Bluebird. It recording a top speed of 484.6 km/hr. [That's 301.1 mi/hr.]



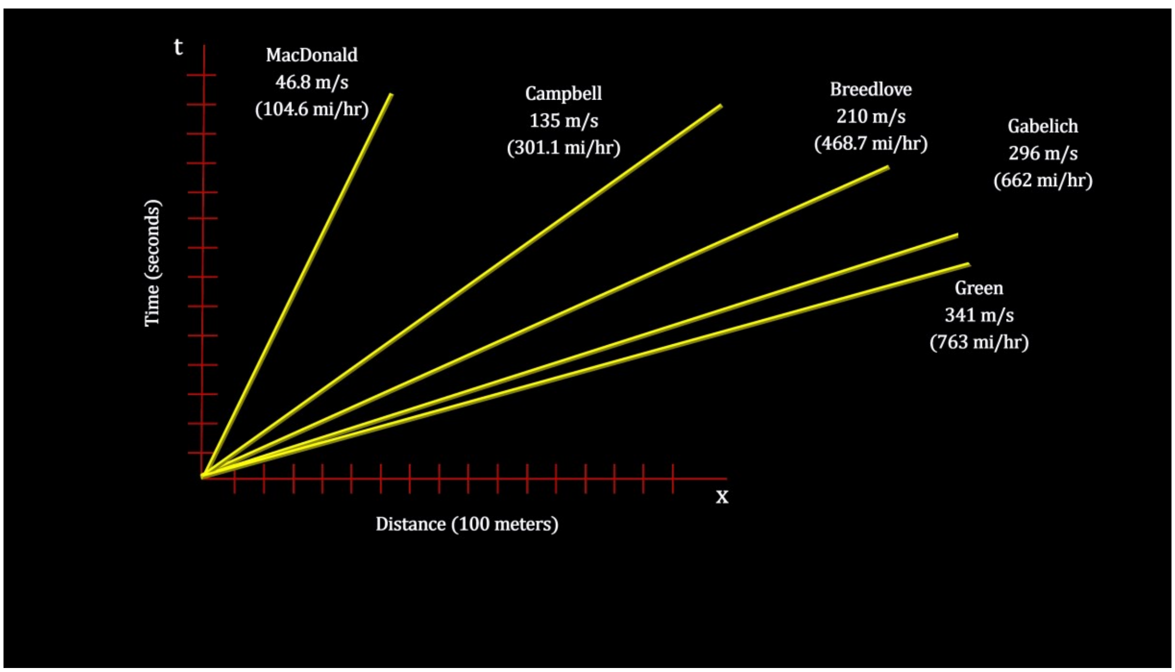
Craig Breedlove steers his jet powered "Spirit of America" across the western Utah salt flats Oct. 13, 1964, to set a world land speed record of 754.3 km/hr. [That's 468.7 mi/hr.] The car had three wheels and was powered by a jet engine.

Gary Gabelich smashed the record at Bonneville Salt Flats in 1970, with The Blue Flame reaching the record speed of 1,066 km/hr. [That's 662 mi/hr.]

And, in 1997, Andy Green drove the Thrust SSC through the sound barrier to 1,228 km/hr. That's 763 mi/hr. This is the current world record for ground speed.

Let's listen to what breaking the sound barrier sounds like.

To graph these speeds, we recalibrate the x axis intervals from 1 meter per mark to one hundred meters per mark.



<u>Speed of sound</u>

Now that we're talking about the speed of sound, let's take a closer look at just what sound is and how fast it travels.

An elastic substance is one that returns to its original shape after having been disturbed – like this ball.

An inelastic medium doesn't – like this pizza dough.

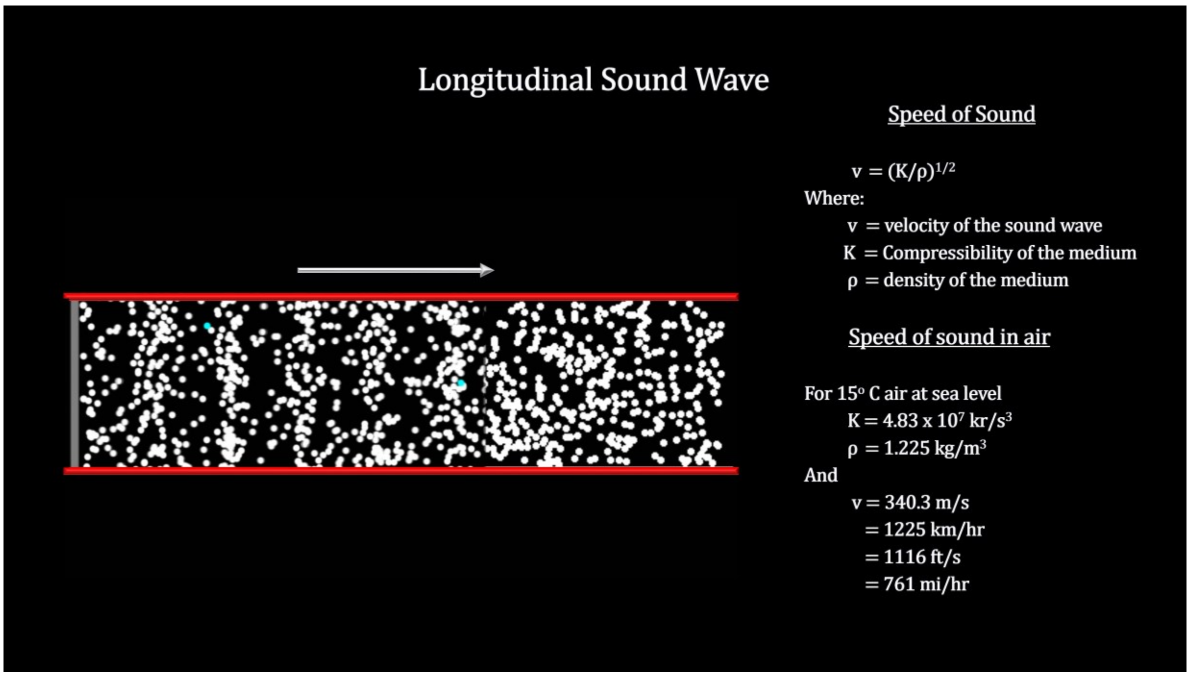
A disturbance in an elastic medium will propagate through the medium. Air is an elastic medium and sound is a disturbance that moves through it.

Sound waves are compression waves. These are waves where the disturbance moves along the line the wave moves. In this animation, each dot represents an air molecule. As the surface on the left moves in, the nearest molecules are compressed. When it moves back, the compressed area becomes rarefied. [The compression followed by rarefaction cycle moves to the right until the end of the medium is reached. Note that the actual molecules remain in their original area. They don't move across the space, but the sound wave along with its energy does.]

How fast the wave moves depends on the characteristics of the medium. In particular, the higher the resistance to compression (its compressibility) the faster the movement, and the closer the molecules are to each other (its density) the slower the movement.

In dry air at 15 °C (That's 59 °F), the speed of sound is 1,225 kilometers per hour or 761 miles/hr.

[It's worth repeating that the speed of sound in a medium is completely determined by these properties of the medium.]

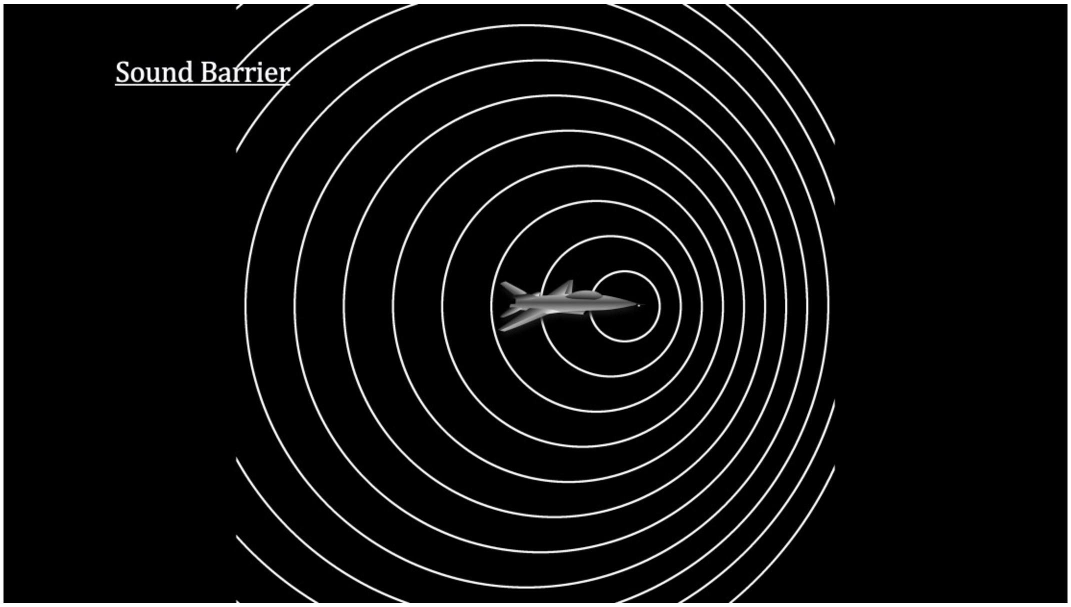


The Sound Barrier

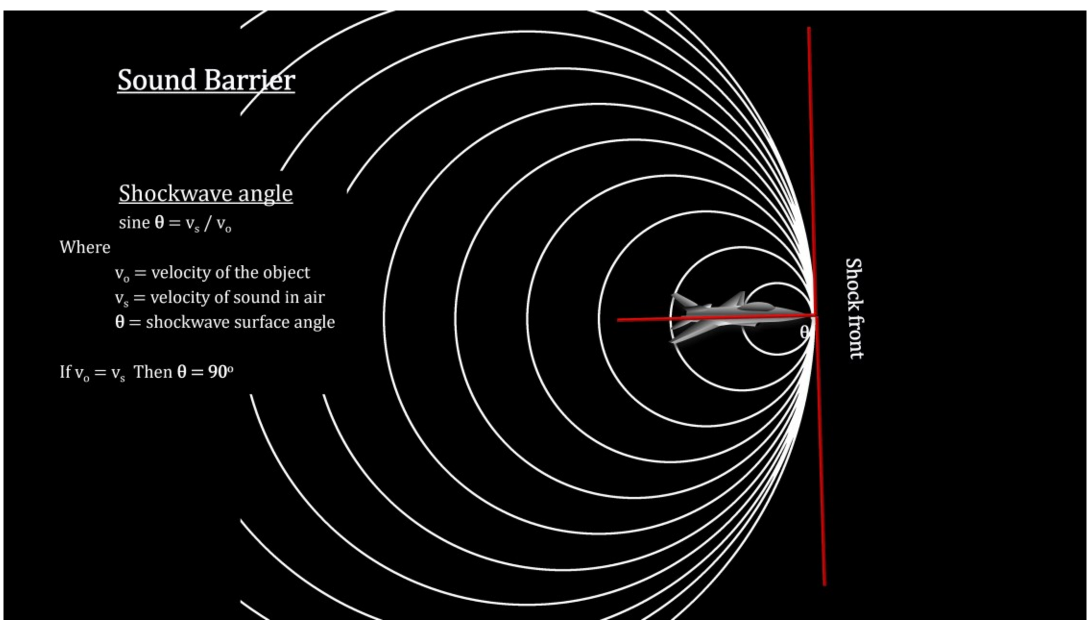
We have seen the car that went faster than the speed of sound. But the speed of sound was more than just a milestone. Early experiences with aircraft traveling near the speed of sound caused so many problems, crashes and deaths that the speed of sound came to be considered a barrier – the sound barrier. [But tragedies did provide the knowledge needed to build aircraft that could stand up to the stresses of extreme flight speeds.]

One of the most famous incidents was the breakup of the de Havilland Swallow and death of its pilot, Geoffrey de Havilland, Jr. in 1946. Structural failure occurred as air built up, pitching the aircraft into a shock stall that placed tremendous loads on the fuselage and wings. The main spar cracked at the roots causing the wings to collapse.

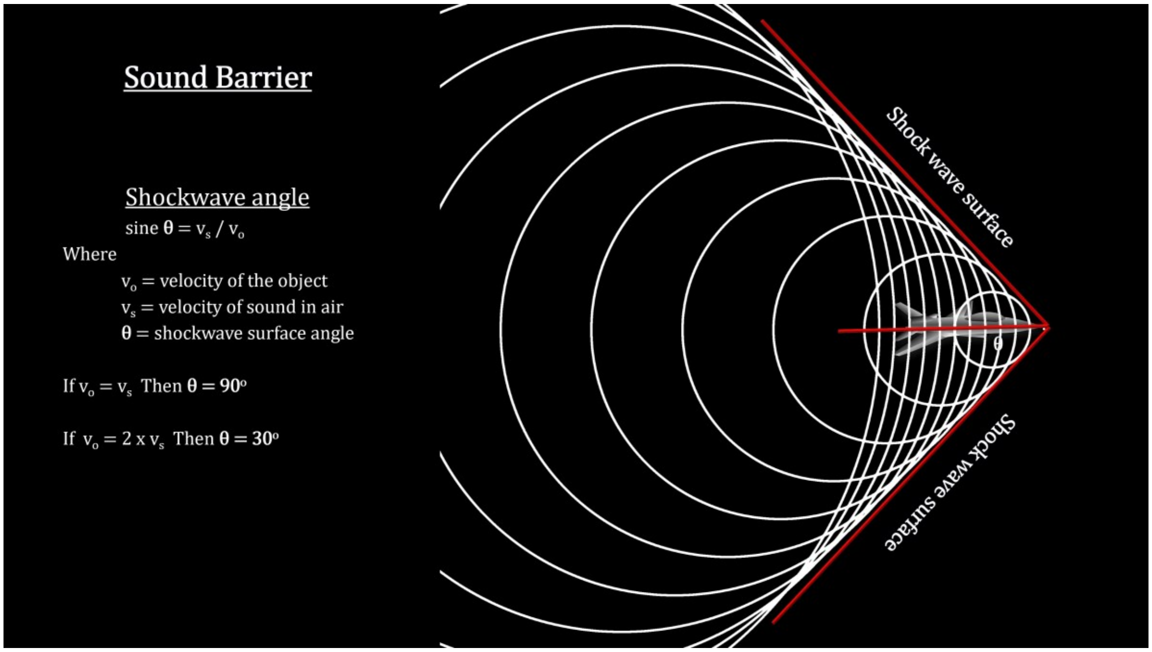
Here's how the sonic boom works. As an object travels through a fluid, like air, it creates waves that encircle it.



As the object approaches the speed of sound, these waves get bunched up at the front of the vehicle creating a shock front that places all sorts of stress on the aircraft.



At the point that the speed of sound is exceeded, the shape of the cone gets narrower. The sonic boom is along the front edge of the cone and follows the aircraft. Observers on the ground will hear one boom. That boom will travel with the jet.



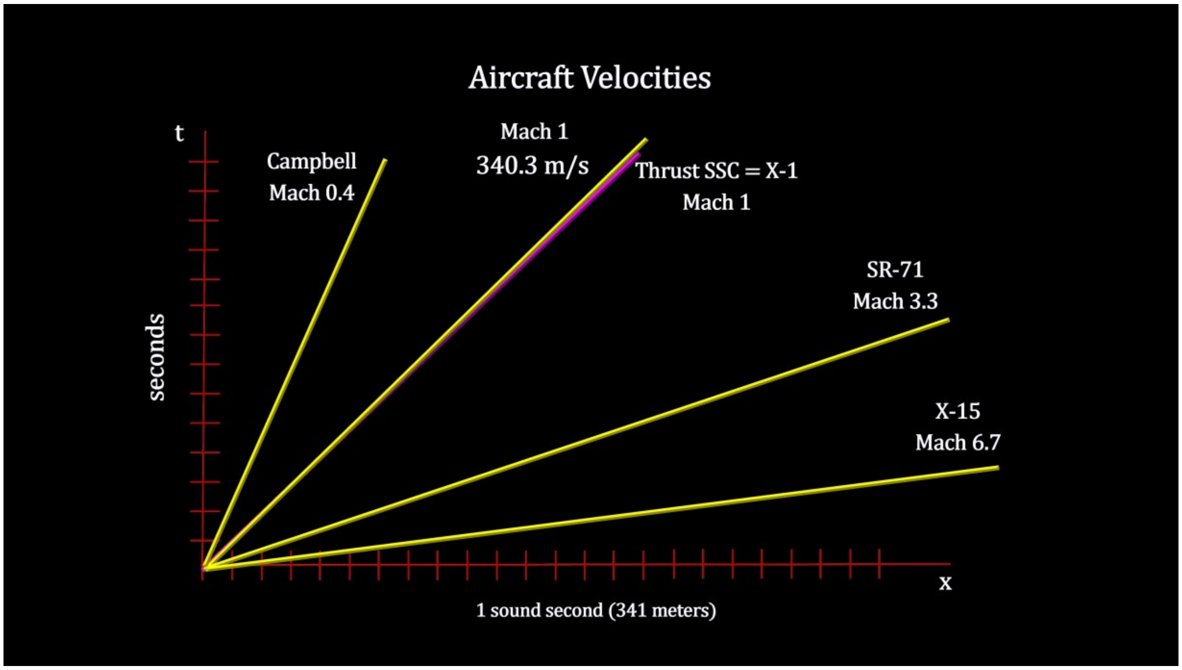
Air Speed Records

Chuck Yeager was the first to break the sound barrier in the X-1. In October 1947, he reached 1,100 km/hr. [That's 684 mi/hr.] We use Mach numbers to signify the multiple of the speed of sound a vehicle travels. This was Mach 1.06.

The Lockheed SR-71A Blackbird set the current world's record for jet aircraft at 3,530 km/hr in 1976 – that's Mach 3.3.

The fasted rocket powered manned aircraft was the X-15. It set the record at 7,258 km/hr in 1967 – that's Mach 6.7

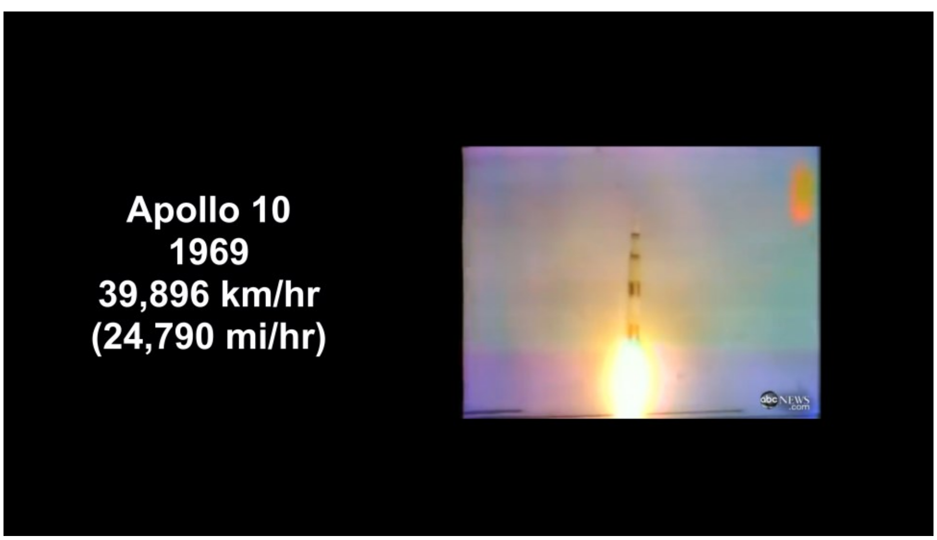
To graph the speeds these cars and aircraft have achieved, we'll need to adjust the units on the x axis again. This time, we'll make each interval on the x axis equal to the distance sound travels in air in one second. That's 341 meters [or 1119 ft.] The line at 45^0s that divides the area in half, is the line that represents the speed of sound in air.



We're now getting close to as fast as humans and our machines can move. The last four we'll cover are all spacecraft.

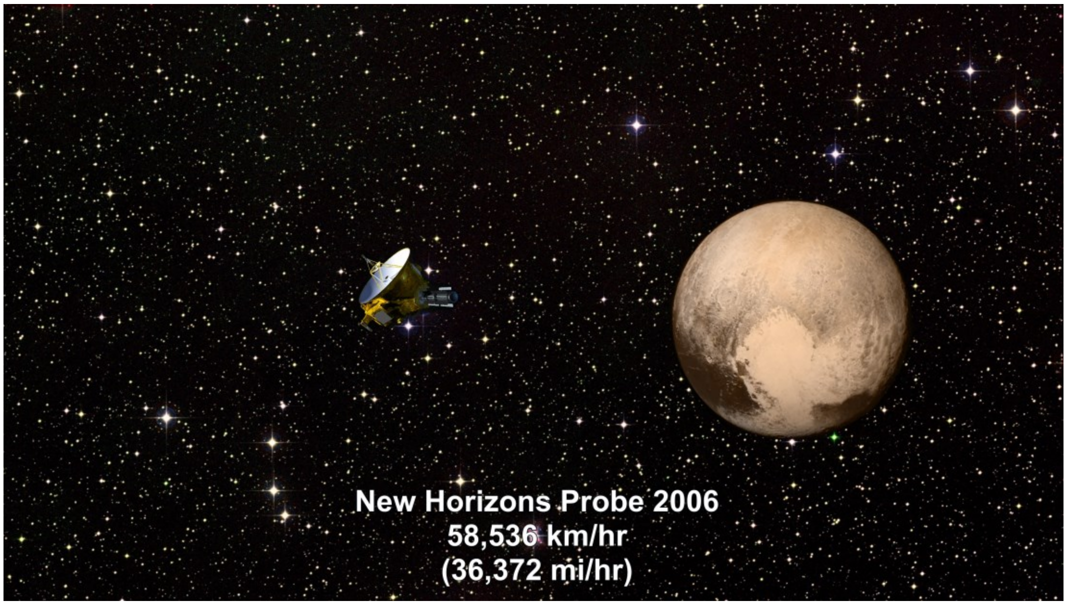
Spacecraft Speed records

Apollo 10 reached 39,896 km/hr in 1969 as it paved the way for man's first landing on the Moon. That's 24,790 mi/hr.



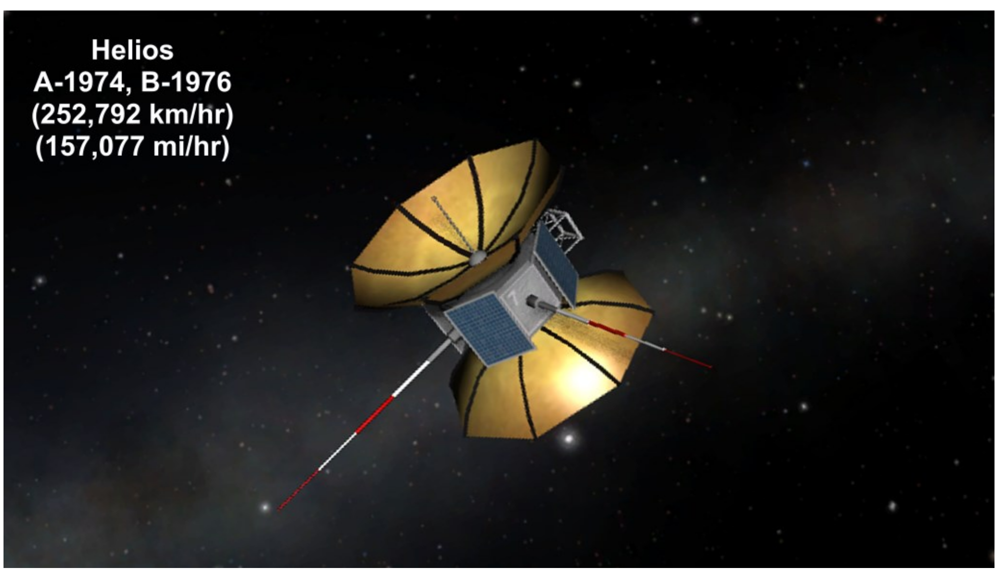
New Horizons probe

The New Horizons spacecraft was launched in 2006 headed for Pluto. It is traveling at 58,536 km/hr [or 36,372 mi/hr] – the record for unmanned space flight as measured relative to the Earth. It started sending back pictures of Pluto in July, 2015.

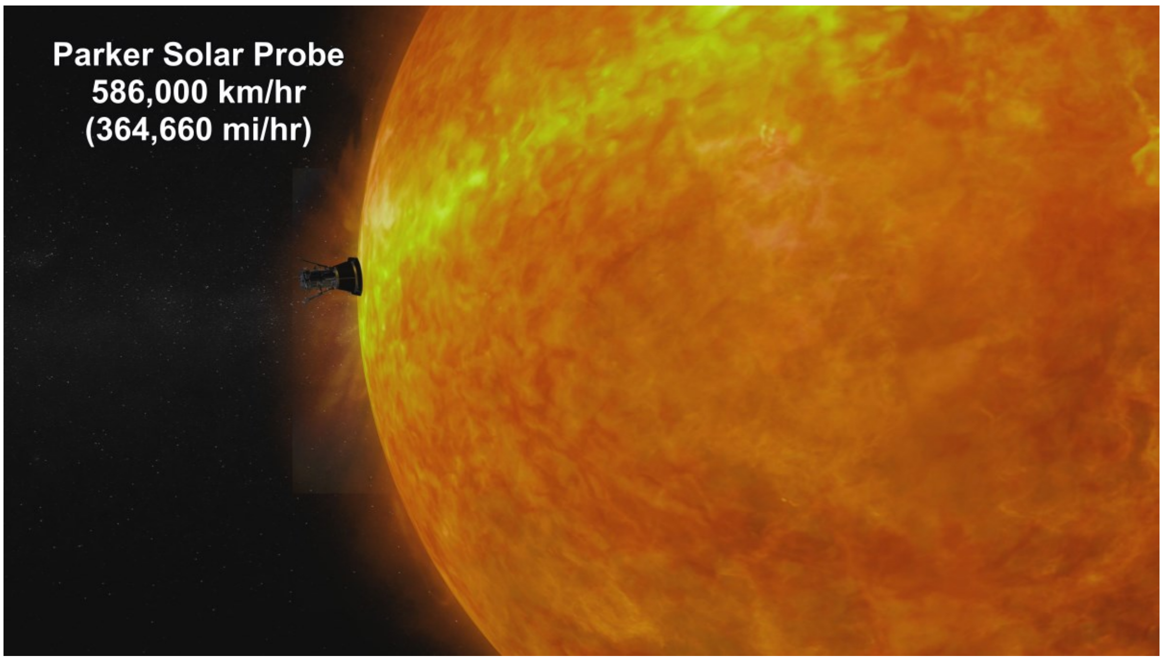


Helios-A & B

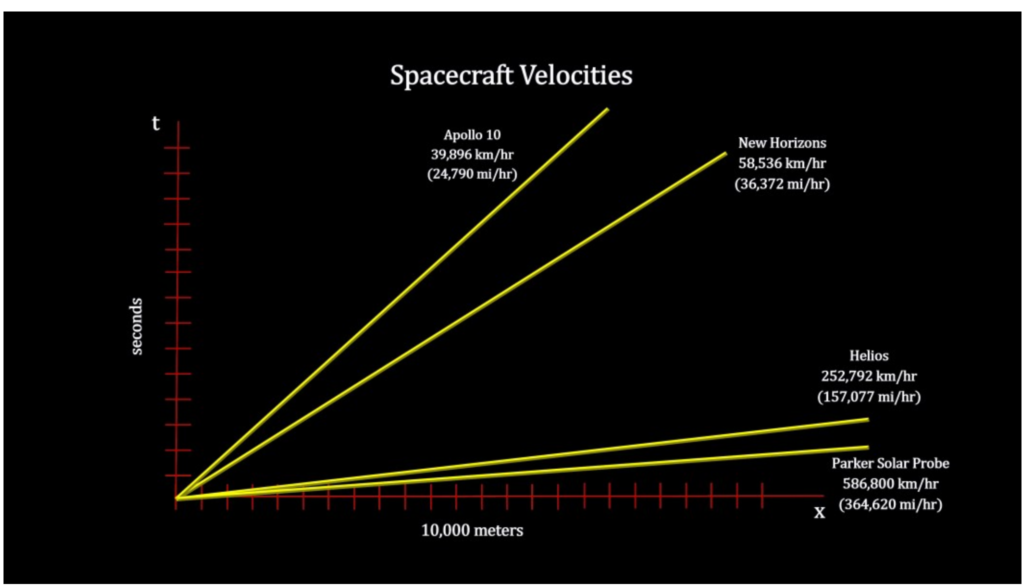
Helios-A and *Helios-B*, are a pair of probes launched into orbit around the Sun in order to study solar processes. Launched on Dec. 10, 1974, and Jan. 15, 1976, the probes are notable for having set a maximum speed record for spacecraft at 252,792 km/hr. That's 157, 077 mi/hr. But this speed is measured relative to the Sun, not the Earth! Note that the Earth's average speed around the Sun is 108,000 km/hr or 67,000 mi/hr.



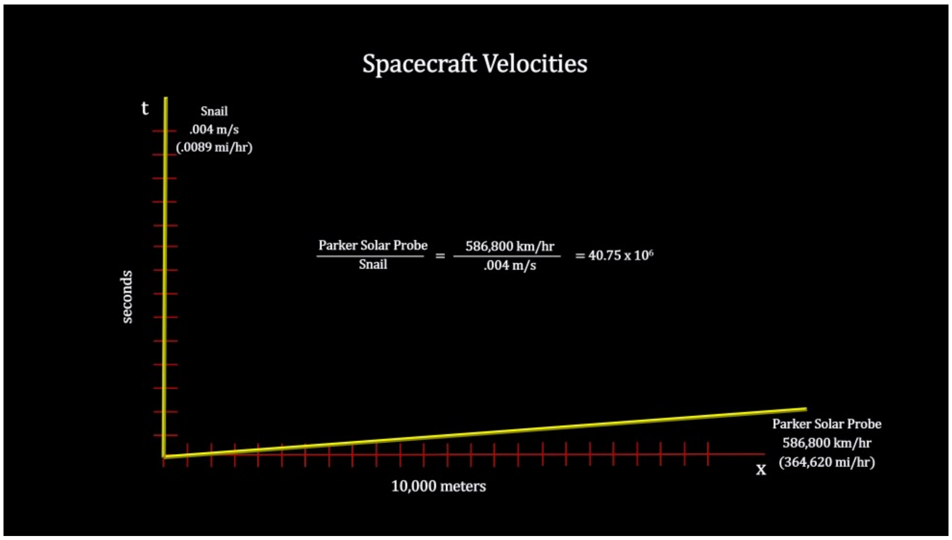
But the current speed record as of mid-year 2022 belongs to the Parker Solar Probe. On November 20th, 2021, it reached a speed of 163 km/s. That's 586,800 km/hr or 364,660 mi/hr as it actually passed through the outer atmosphere of the Sun! It reached this speed after getting a gravity assist from Venus a month earlier. This is the first time in history, a spacecraft has touched the Sun's corona where it sampled particles and measured its magnetic fields. This record is expected to stand until September 2023 when the probe will beat its own record on its 17th orbit of the Sun.



At these speeds, we have to increase the distance interval again. We'll set it at 10 km per mark. That's 6.2 miles.



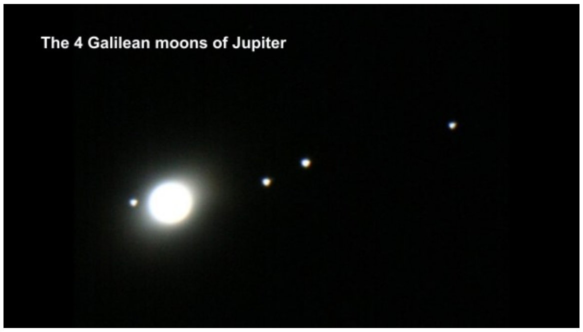
Parker is moving over 40 million times faster than the snail in my backyard.



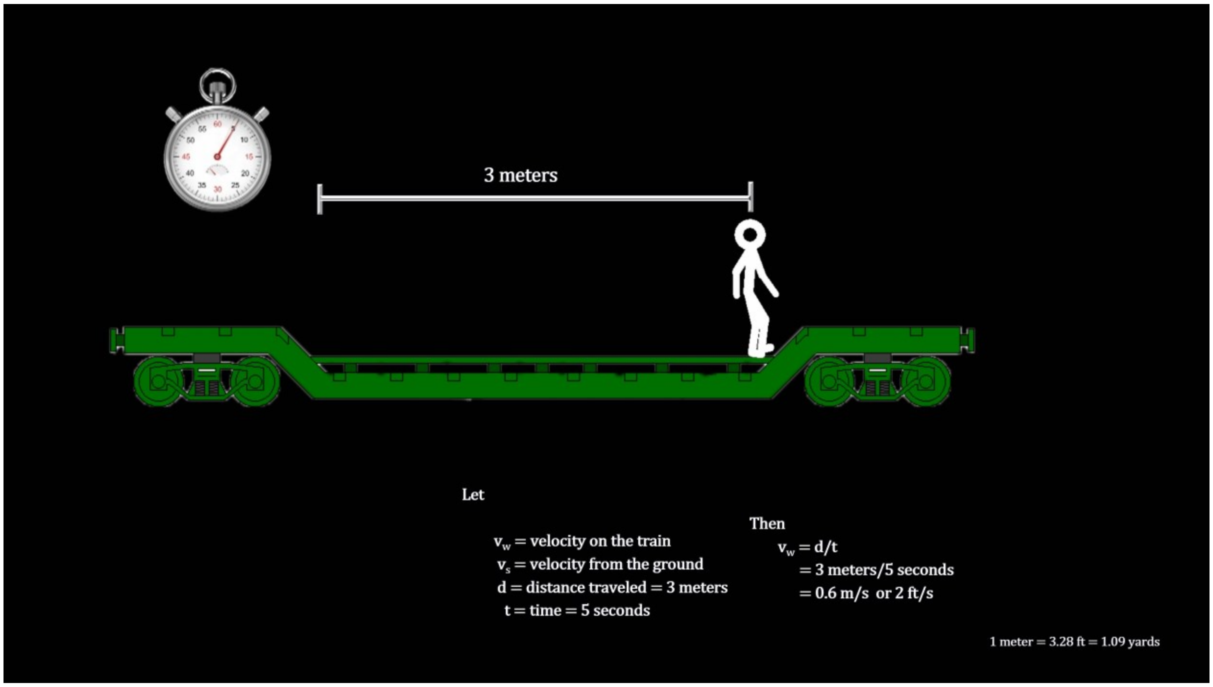
Galilean Transformations **[Music**: Mozart – Violin Concerto No 5 Turkish II**]**

All our speeds so far except for the last two, were relative to the surface of the Earth. In the time before we knew the Earth was spinning on its axis once a day, and rotating around the sun once a year, everyone thought that the universe had one preferred frame of reference against which all other speeds could be measured. That preferred frame was the Earth, the center of the universe.

But once Galileo spotted the moons around Jupiter, another approach was needed.

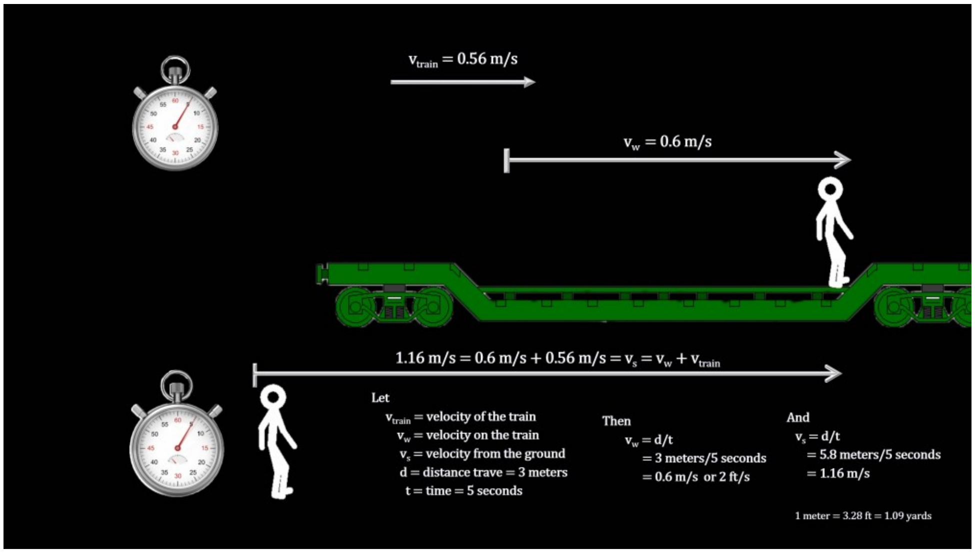


We'll use a train example. Let's measure the speed of the person walking on the train. We'll use the same measuring technique we used for the snail in my backyard. The person on the train sets his clock to zero; marks his starting spot; walks down the car; stops the clock; and marks the second point. Now he just measures the length of the line and divides by the time. In this example he went 3 meters in 5 seconds for a speed of .6 m/s.



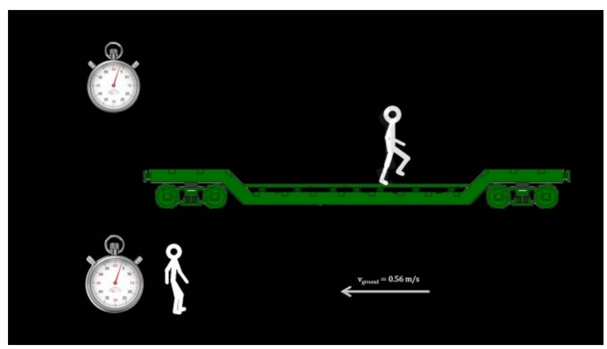
Now picture the train car moving slowly to the right at 2 km/hr. or .56 meters per second (remember that a meter is just a bit longer than a yard). This is the speed as measured by a person on the ground. We'll call it v'.

We then repeat the measurement for the observer on the ground who's watching the train go by. He sets his clock to zero at the same time the rider on the train does; he marks the rider's starting spot; he watches the rider move down the moving car; he stops the clock when the rider does; and he marks the second point. Now, using the same process, he just measures the length of the line and divides by the time. In this example the rider went 5.8 meters in the same 5 seconds for a speed of 1.16 m/s.

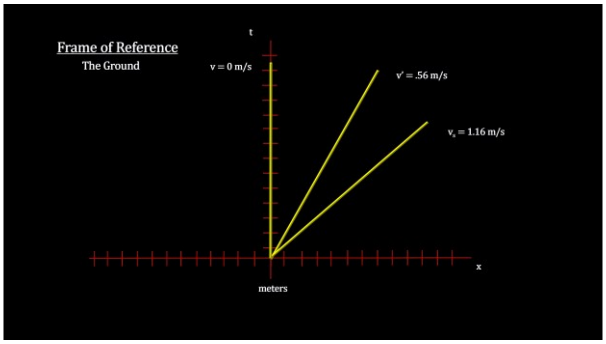


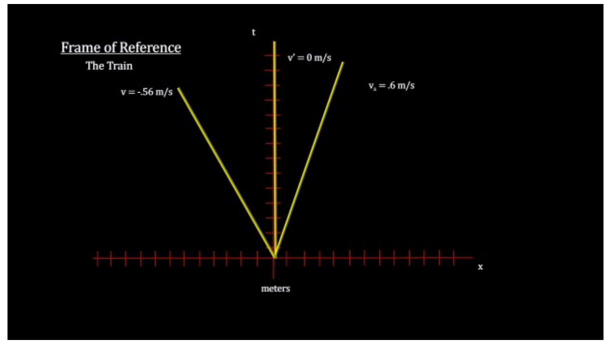
Who is correct? Is he moving at .6 m/s or almost double that speed at 1.16 m/s? In the old system, before Galileo, you could argue that the observer on the ground was correct.

But in the actual world of equal reference frames, and total motion relativity, both are correct. In fact, we could have done it from the point of view of the train instead of the person on the ground. In that case, it is the person on the ground that is moving at .56 m/s to the left, instead of the train moving to the right.

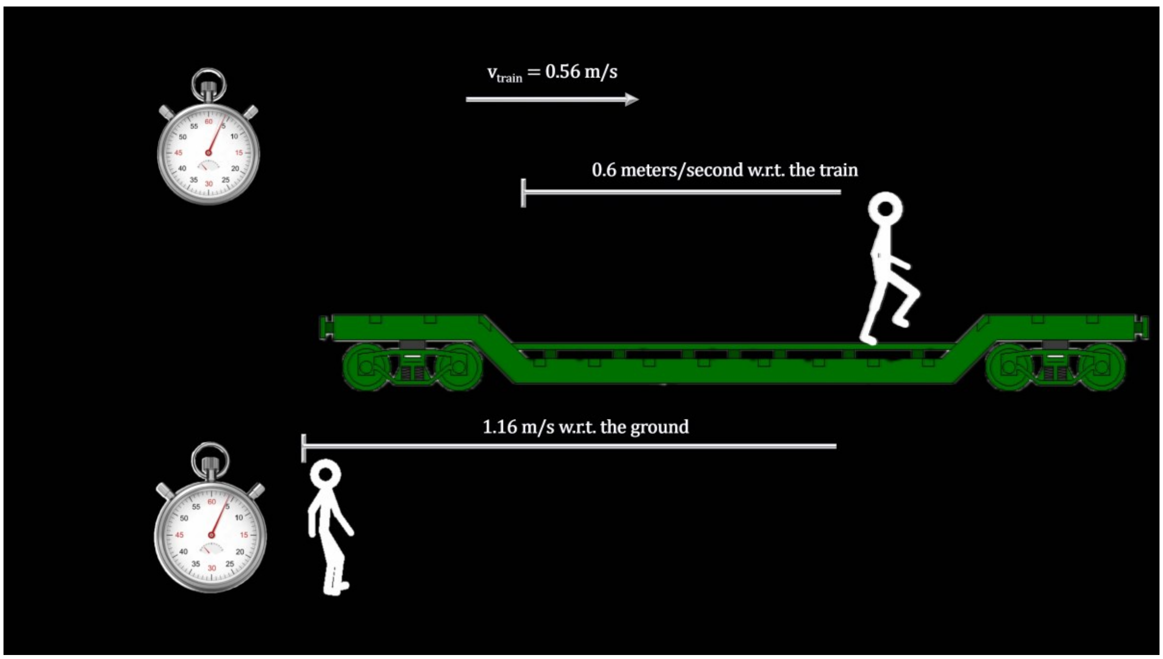


If we put this on our space-time graph, we see the train moving as the inertial frame velocity v', and the person walking with the velocity 1.16 m/s. Now just rotate the velocity lines to make the train standing still. This turns it into the space-time graph for the train's frame of reference. Here we see that the ground is moving backwards at 0.56 m/s, and the person on the train is moving at 0.6 m/s.

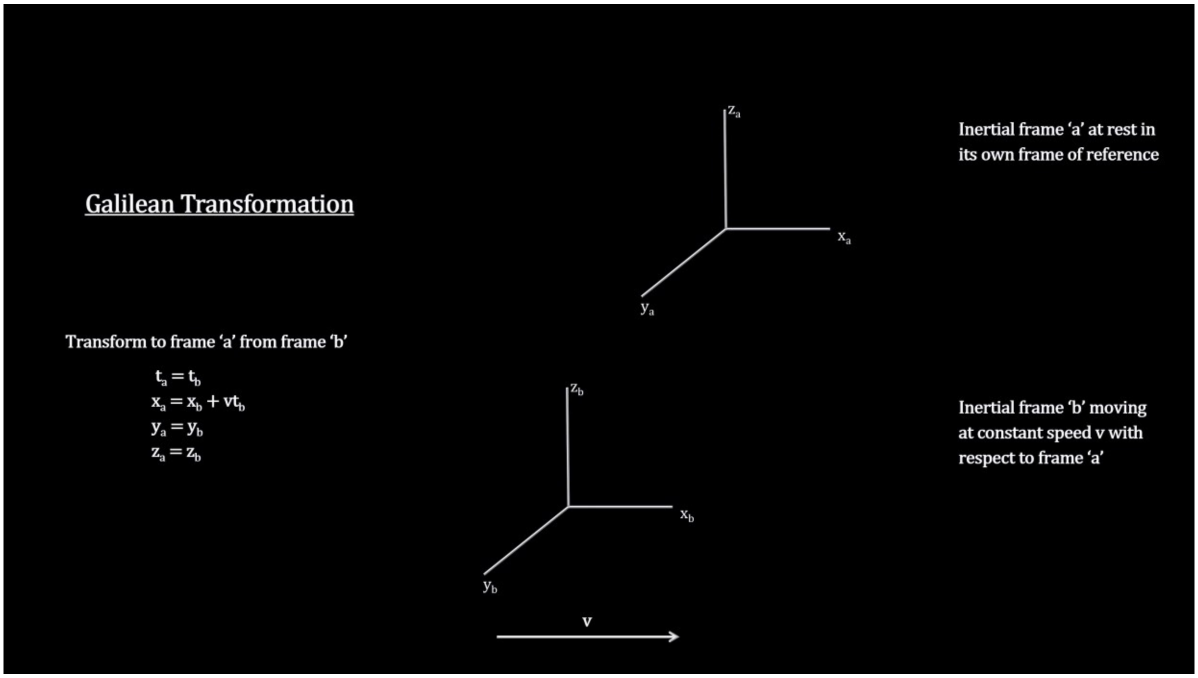




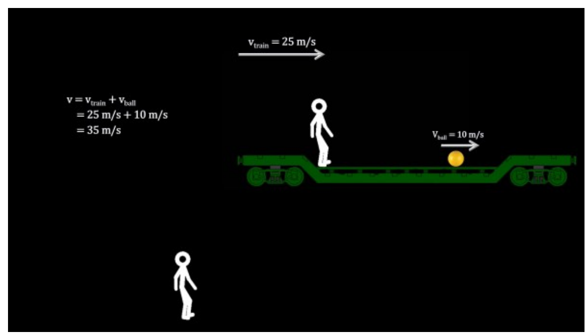
With this in mind, to be completely accurate, the statements need to be worded as "The person on the train is moving at .6m/s with respect to the train.", and "The person on the train is moving at 1.16 m/s with respect to the ground."



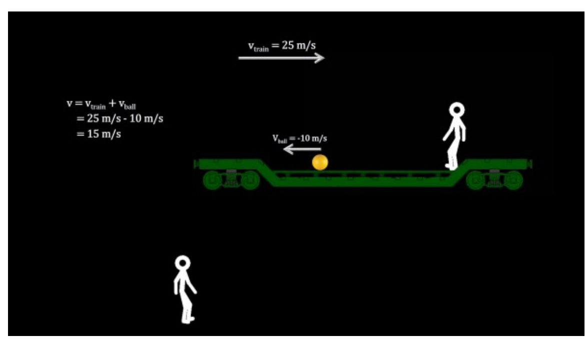
You can see that we are simply adding the speed of the train to the speed of the person with respect to the train. This is the Galilean transformation between two reference frames moving at a constant speed with respect to each other. These are called inertial frames because they are not experiencing any acceleration. In this model, time flows at the same rate in all inertial reference frames, and all motion is relative. The Galilean transformations give us the equations for converting from one frame to another.



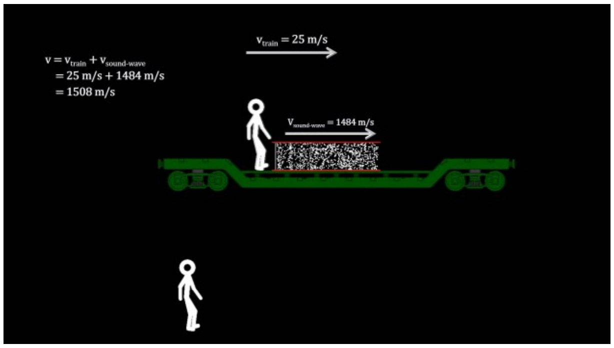
Let’s look at another example. Here the train is moving faster at 25 m/s. The person on the train kicks a ball in the direction of the train movement and measures its speed at 10 m/s. The person on the ground would add this to the speed of the train and get 35 m/s.

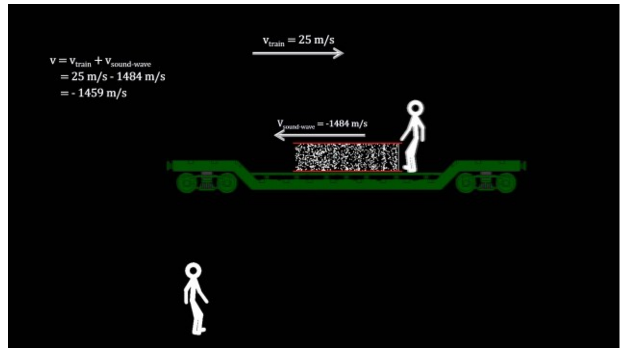


Now if the person kicks the ball in the opposite direction, the person on the ground would subtract the speed of the ball from the speed of the train. He would see it moving at 15 m/s. [In fact, if the boy had kicked the ball backwards at 25 m/s (the speed of the train), the person on the ground would see it as standing still!]

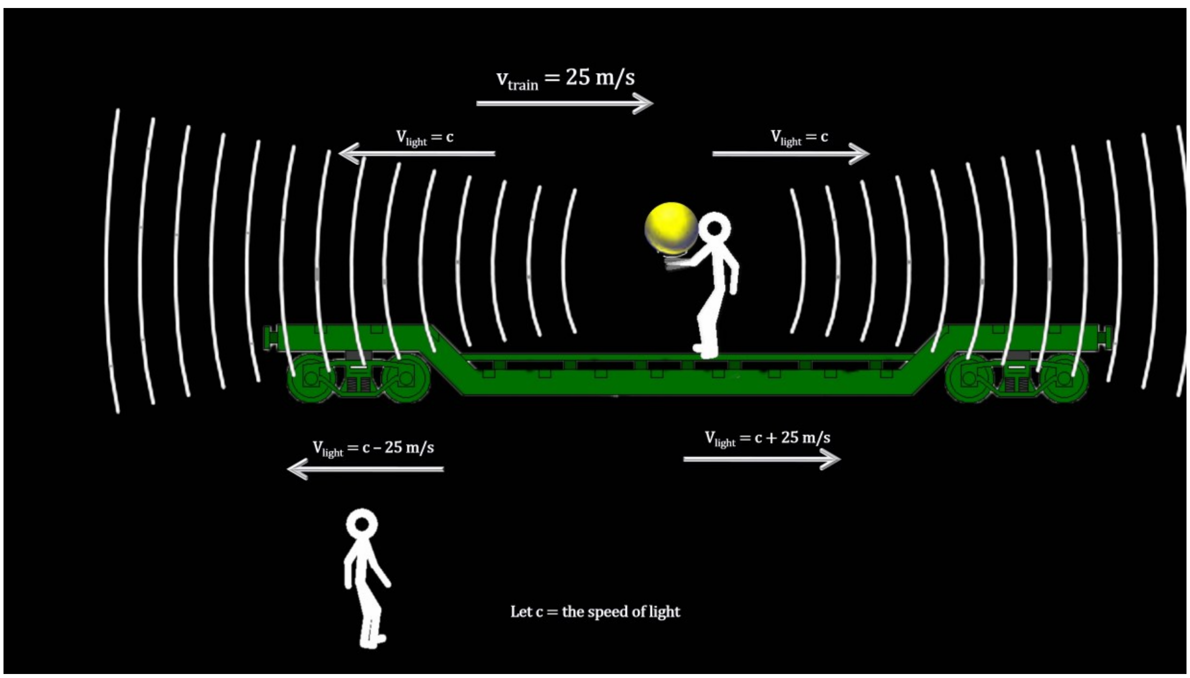


Here’s another example that illustrates that it doesn’t matter what is moving. Suppose the person on the train kicks a water container initiating a sound wave in the water moving in the direction of the train. He would measure the speed of sound in water as being the same when he kicks it forward and when he kicks it backward. The speed of sound in water is around 1,484 m/s. The person on the ground would measure the forward moving wave at 25 m/s faster than that (1,509 m/s), and he would measure the backward moving wave at 25 m/s slower than that (1,459 m/s).





It followed that if it were a lightbulb that the person on the train turned on, he would see the light moving in the direction of the train and the light moving in the opposite direction of the train to be the same 300,000,000 m/s = c. But the person on the ground would measure the light moving with the train as just a little faster than c (c + 25 m/s = 300,000,025 m/s), and the speed of light traveling against the movement of the train just a bit less than c (c - 25 m/s = 299,999,975 m/s).



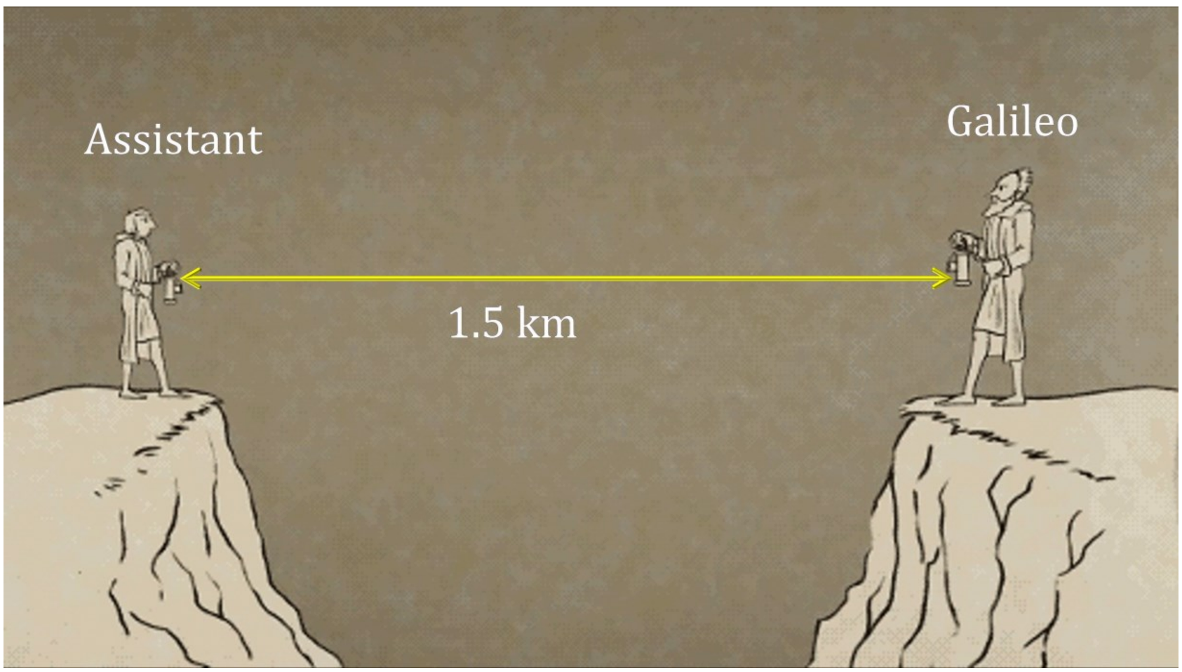
This view stood the test of time from Galileo until the mid-1800s because no one could measure the speed of light and no one had instruments sensitive enough to measure these small differences in the speed of light.

Speed of Light - Early Measurements

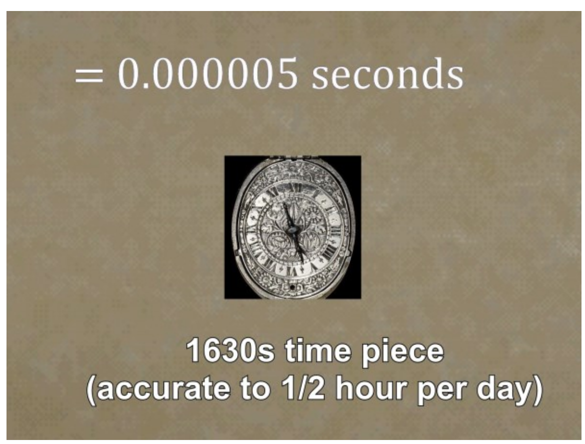
Galileo's Speed of Light

Galileo himself tried to measure the speed of light. His method was quite simple. He and an assistant each had lamps which could be covered and uncovered at will.

They climbed to the tops of hills around 1.5 km apart. Galileo would uncover his lamp, and as soon as his assistant saw the light, he would uncover his. By measuring the elapsed time until Galileo saw his assistant's light, factoring in reaction times calculated earlier, and knowing how far apart the lamps were, Galileo reasoned he should be able to determine the speed of the light.



Given how fast light is, we know that the time interval Galileo was trying to measure was around 5 microseconds. The clocks available to him at that time could not measure that tiny a time interval. His conclusion about light speed was: If it's not instantaneous, it is extraordinarily rapid.

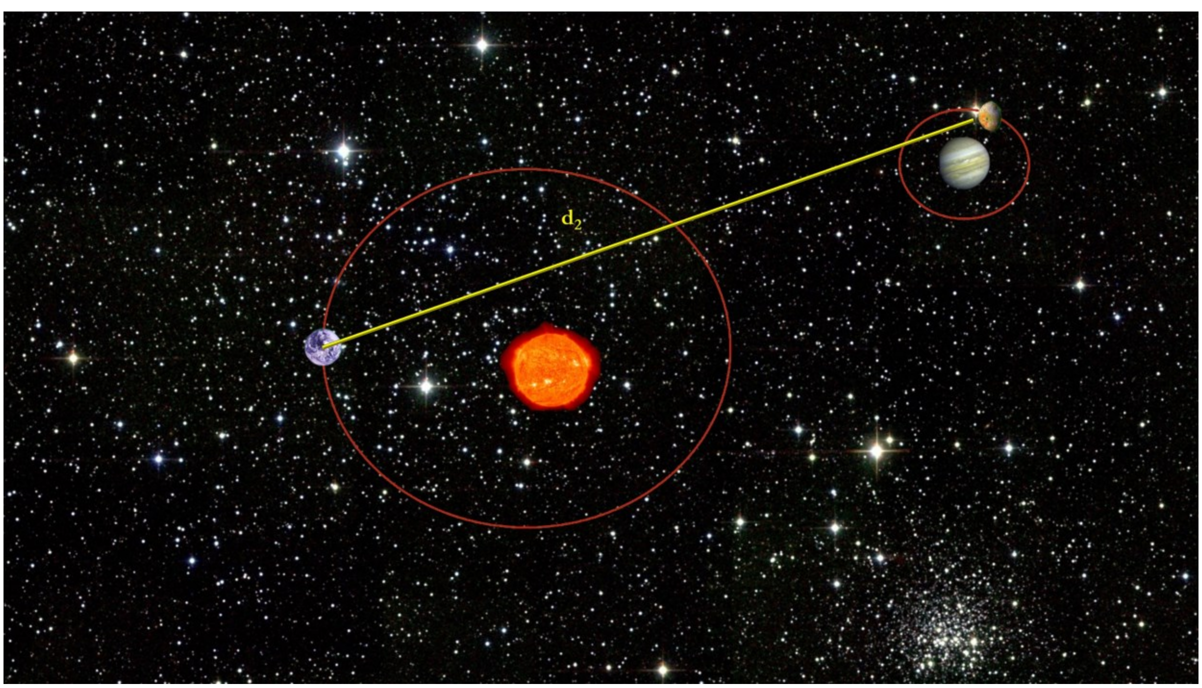


Ole Roemer's Speed of Light

Until early in the 18th century, it was generally believed that the speed of light was infinite. This view was held by Aristotle in ancient Greece, and vigorously argued by the French philosopher Descartes and agreed to by almost all the major thinkers over the two thousand years that separated them. Galileo was an exception. But, as we just saw, when he tried to measure the speed of light, he failed.

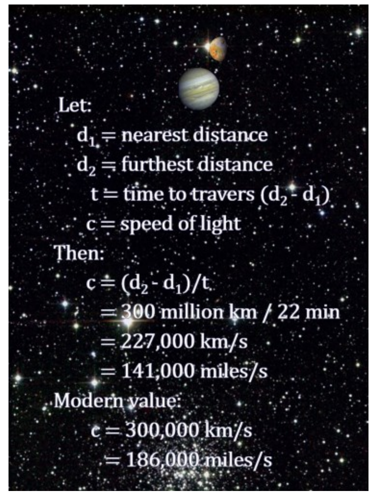
But Galileo did set the stage for the first measurement. After he discovered the first 4 moons of Jupiter, he suggested that the eclipse of the moon Io would make a good celestial clock that navigators could use to help determine their location.

In 1676, the Danish astronomer Ole Roemer was compiling extensive observations of the orbit of Jupiter's moon Io to see if Galileo was correct. The satellite is eclipsed by Jupiter once every orbit, as seen from the Earth. Timing these eclipses over many years, Roemer noticed something peculiar. The time interval between successive eclipses became steadily shorter as the Earth in its orbit moved toward Jupiter and became steadily longer as the Earth moved away from Jupiter. In a brilliant insight, he realized that the time difference must be due to the finite speed of light. That is, light from the Jupiter system has to travel farther to reach the Earth when the two planets are on opposite sides of the Sun than when they are closer together.



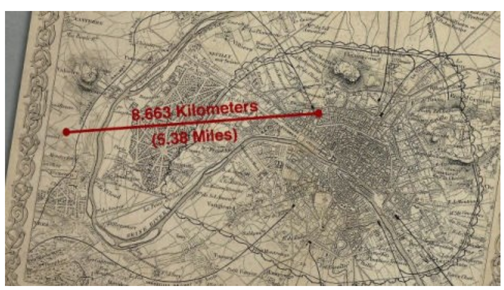
Using what he knew about planetary orbits from Kepler, he estimated that light required twenty-two minutes to cross the diameter of the Earth's orbit. The speed of light could then be found by dividing the diameter of the Earth's orbit by the time difference.

The actual math was done by others after Roemer's death in the early 1700s. Those who did the first arithmetic, found a value for the speed of light to be 227,000 km per second or 141,000 miles per second. Not too bad for the instruments of the 18th century. The modern value is 300,000 km per second or 186,000 miles per second.

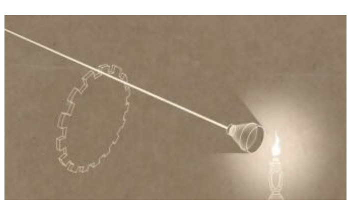


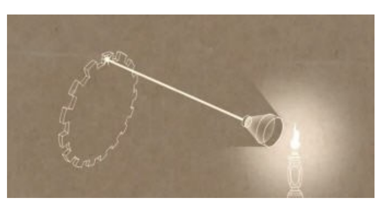
Fizeau's Speed of Light

Then in 1849, a French physicist named Antonio Louis Fizeau did measure the speed of light. As Galileo had done, Fizeau chose two high points, but in his case, they were a good deal further apart at just over 8 ½ km.



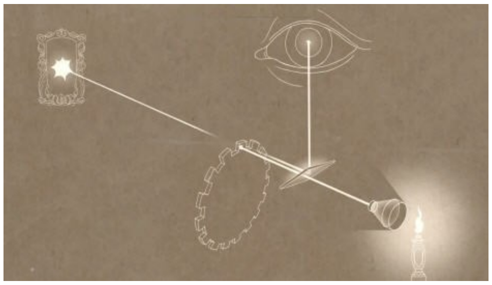
In place of covering and uncovering lanterns, he used shining light through the edge of a toothed wheel. Whether the light beam got through the edge of the wheel depended on the wheel's position. If one of the teeth was in front of the light beam, it was blocked. If one of the gaps was in front of the light beam, it got through.

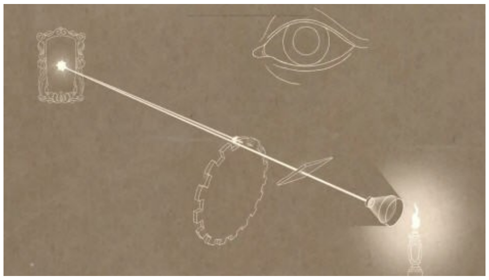




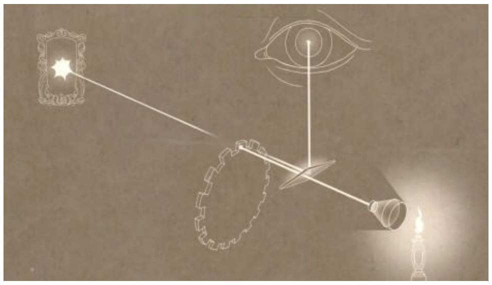
To avoid the problem of human reaction time, Fizeau placed a mirror on the far hill instead of a person. He also added a partially reflective mirror to guide returning light to his eye.

When Fizeau set the wheel spinning at a slow speed, a flash of light that shot through one of the gaps would travel to the mirror on the distant hilltop, get reflected, and travel back to Fizeau so fast that the gap was still in place. The wheel had not had time to move a tooth in the way of the beam of light to block its return.





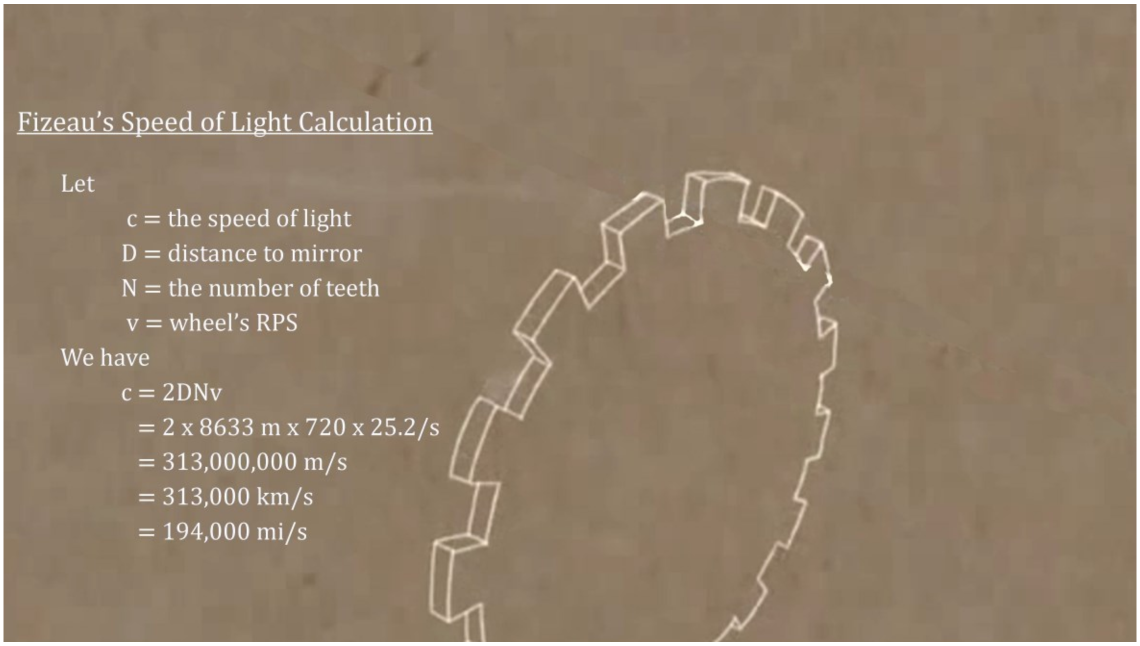
Fizeau then increased the speed of the wheel until the light moving through each gap to the mirror and back encountered a tooth instead of the gap on its return. This blocked the light from getting to his eye.



Fizeau continued to make the wheel spin faster until, eventually, the light would shoot through a gap and, by the time it travelled to the mirror and back, the tooth had moved completely across the line of sight. The beam of light returned just in time to move through the next gap and he could see it again.

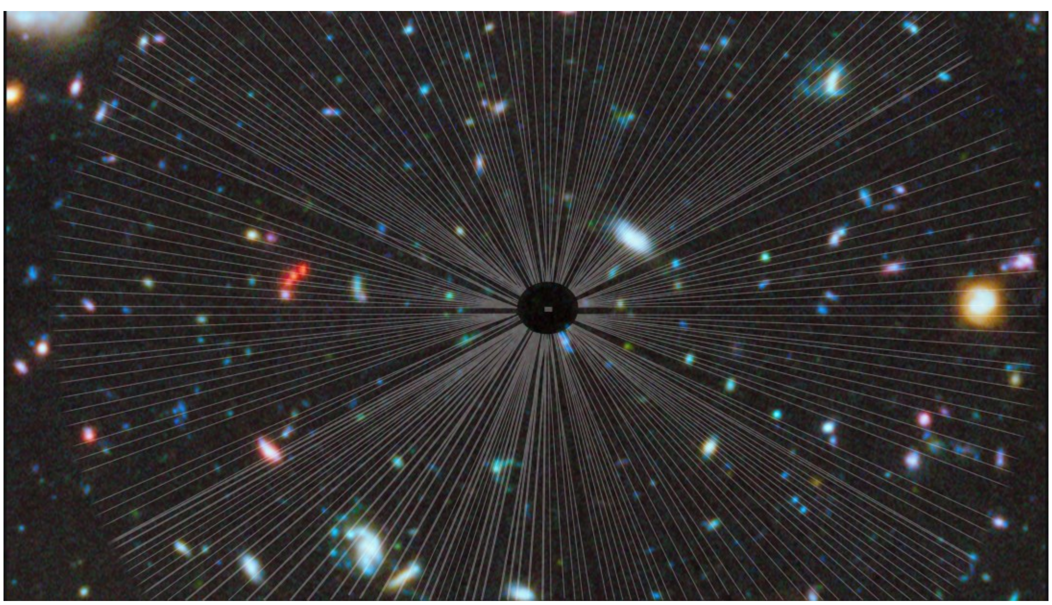
In supper slow motion it would look like this. [The wheel has 720 teeth.] Knowing the number of teeth and the rotation rate, Fizeau could calculate the time it took for one tooth to move out of the way of the returning light. Dividing the distance by the time gave him the speed of light at 313,000,000 m/s. He was only off by 4%.

[At 25.2 revolutions per second, the light that travels 17,266 km to the mirror and back arrives just after the tooth has moved 55 microseconds - which is just enough to get the tooth out of the way so the light could pass through.]

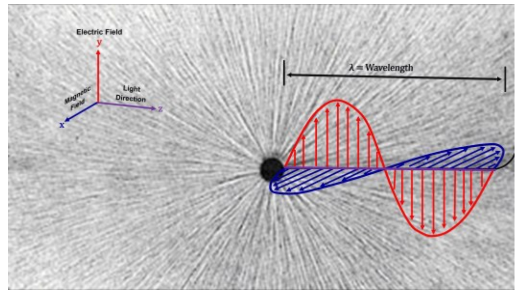


Maxwell's Speed of Light **[Music**: Joseph Haydn – Symphony No 98**]**

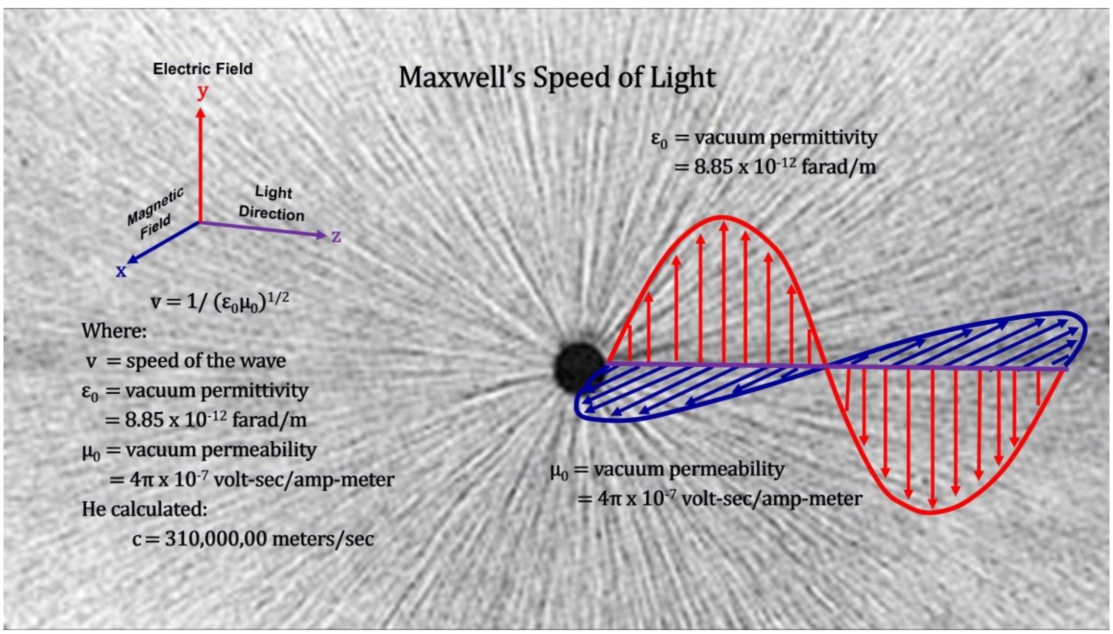
In the 1860s, people like Michael Faraday, Andre Ampere and James Maxwell and others were studying electric and magnetic fields. Maxwell proposed that the existence of an electric charge filled empty space with an electric field.



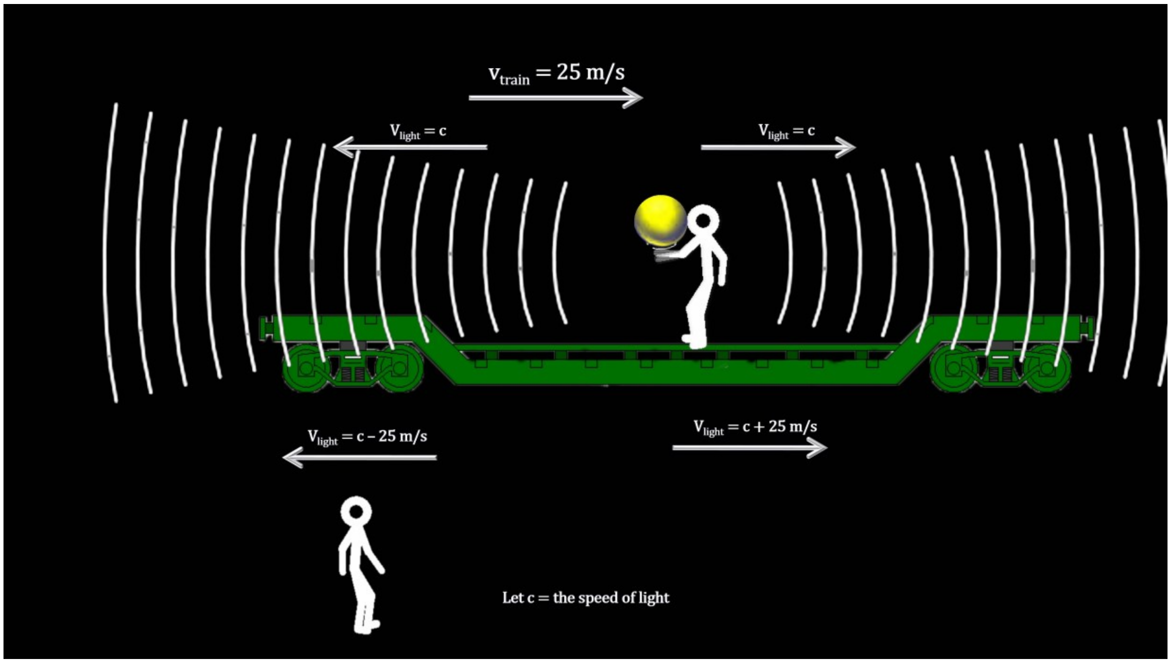
Accelerating the charge causes the electric field to change. Furthermore, he showed that a changing electric field created a magnetic field. And a changing magnetic field created an electric field. So, the accelerated electron creates a disturbance in the electric field that propagates itself through space as an electromagnetic wave.



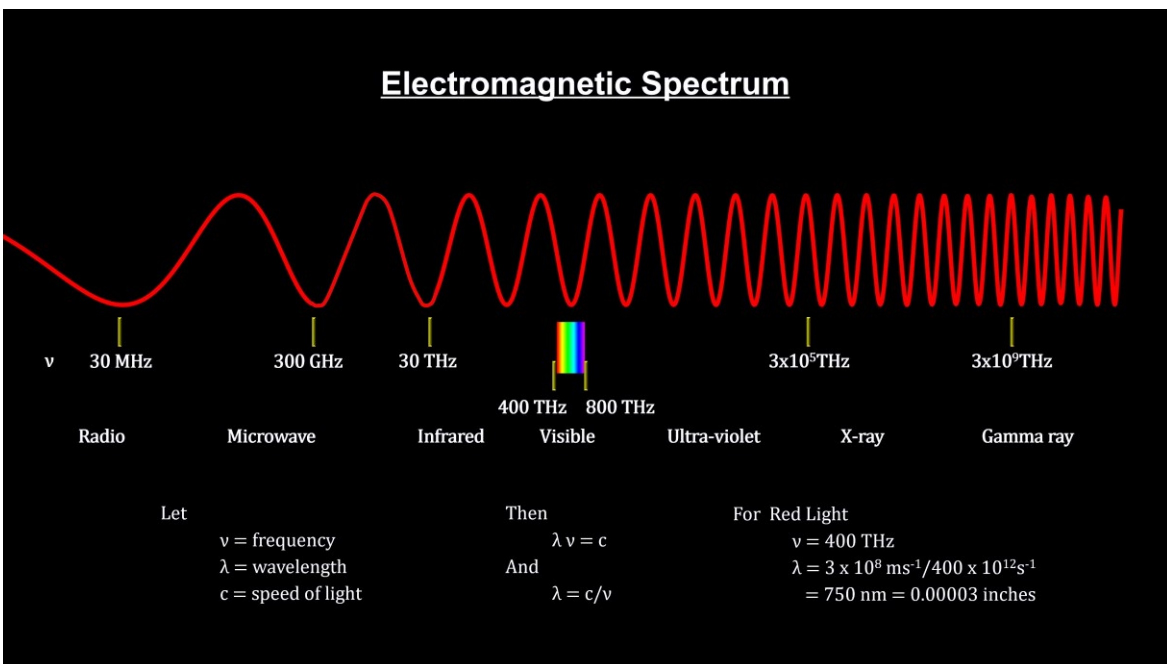
Earlier, Faraday had measured the resistance of empty space to the forming of an electric field called permittivity and Ampere had measured the resistance of empty space to the forming of a magnetic field called permeability. In 1864, using their numbers, Maxwell calculated the speed of his waves at around 311,000 km/s or 193,000 mi/s. This was in good agreement with Fizeau's for light [313,000 km/s.]. Maxwell had demonstrated that light is indeed an electromagnetic wave.



This was a remarkable achievement, but it created a problem. The Galilean transformation would have the speed of light adjusted for the relative speed between reference frames. But Maxwell's value is a constant! It does not change for the observer on the train and the observer on the ground.

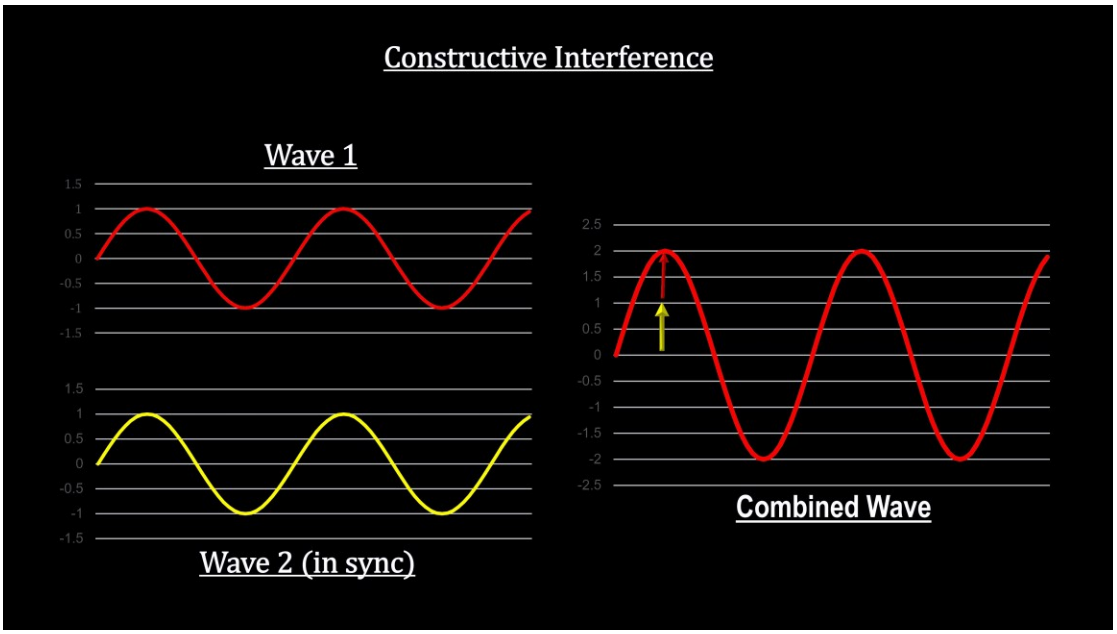


Given that the speed of a wave is equal to its wavelength times its frequency, to resolve this conflict, we need an exact measurement for these two quantities. For visible light frequencies like the color red [f = 461 THz] we see that we would need to measure wavelengths on the order of 650 nm. That's less than 3 one-hundred thousandths of an inch. In the 1800s, there was no way to measure lengths this small. That changed when Albert Michelson invented the interferometer.

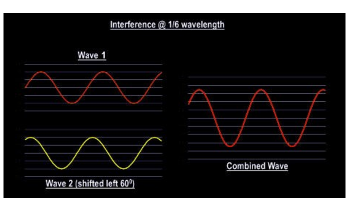


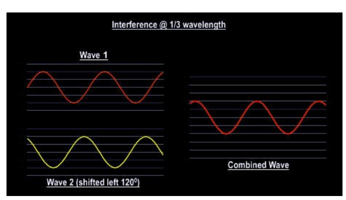
Michelson Interferometer

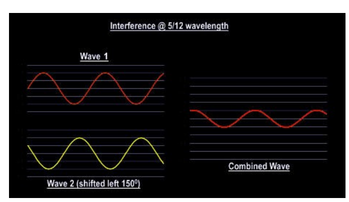
In 1881, Albert Michelson found a way to measure extremely small differences in the speed of light. This is precisely what we need to verify the Galilean transformation for light. His basic idea revolved around light interference patterns. For example, if we combine two waves that are in synch with each other, they reinforce the output wave.



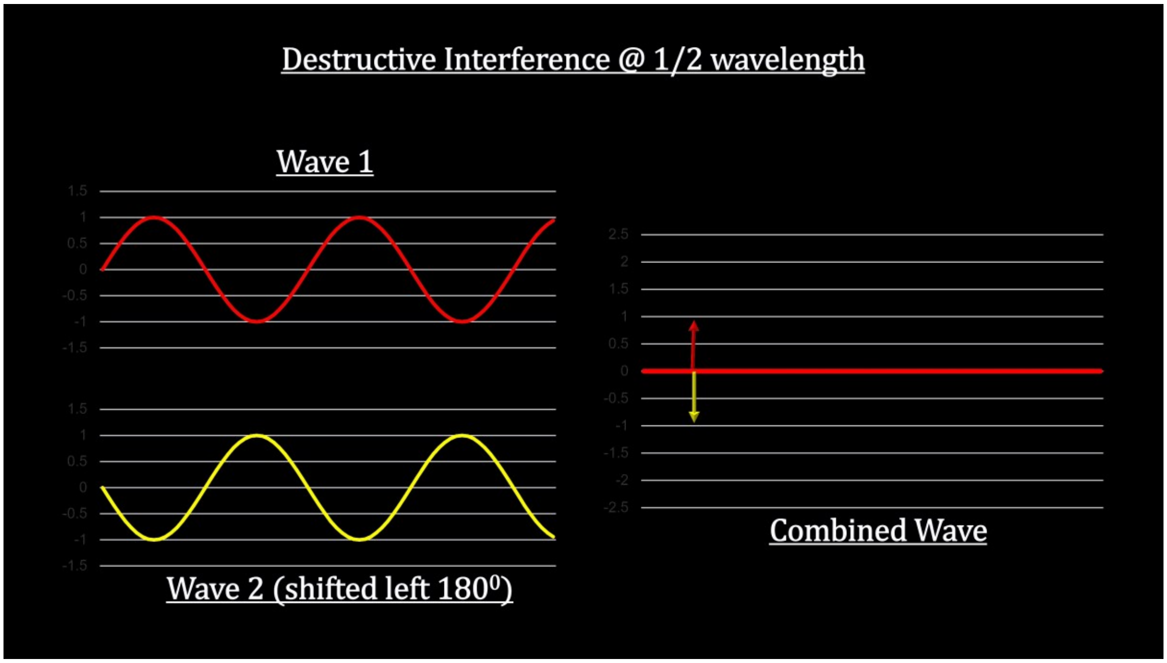
As we shift one of the input waves, we see the output deviate from the maximum reinforcement.



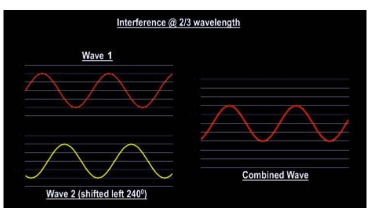


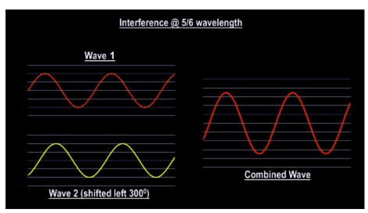


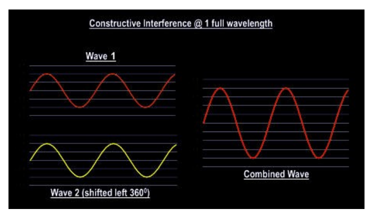
As we reach ½ of a wavelength out of synch, we get total destructive interference. The waves in effect, cancel each other out.



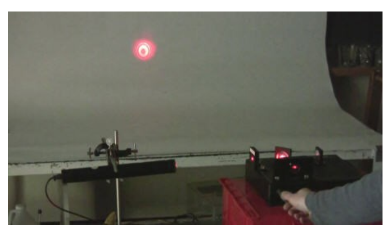
If we keep going, we move back into complete constructive interference as we reach one full wavelength.



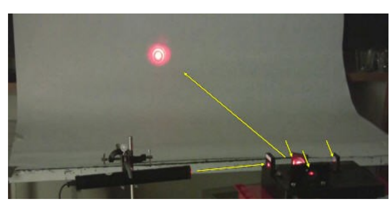




What Michelson did was to leverage this light interference behavior in what we now call an interferometer. Here's one from the MIT physics lab.



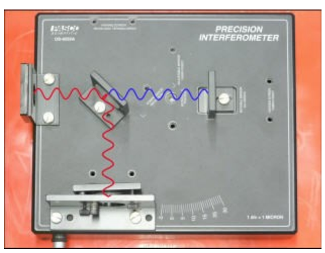
A light source shines light into the interferometer where it is split and reconstructed using mirrors. The reconstructed light shows up on a screen.

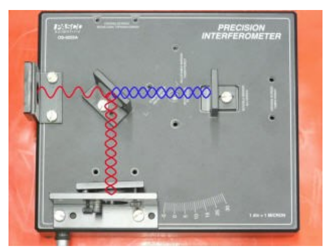


[The characteristics of the interference pattern depend on the nature of the light source and the precise orientation of the mirrors and beam splitter.] The bright lines indicate areas of constructive wave interference and the darker lines indicate areas of destructive wave interference.

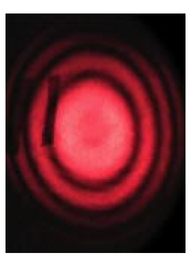
Moving the mirror changes the positions at which the light constructively and destructively interferes.

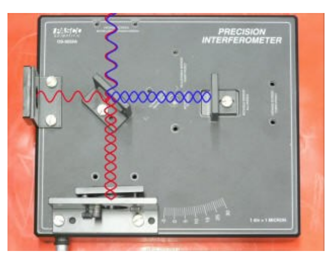
Here's how the light flows through the apparatus. First, the incoming light source is split into two by a partially reflective mirror. These two beams then reflect off of mirrors and recombine at the splitting point.



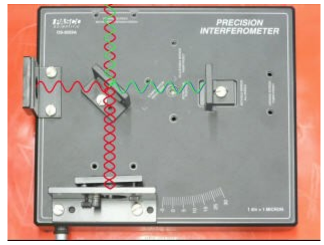


If the distances traveled are exactly equal, they will be in sync when they recombine. This produces the maximum constructive interference.

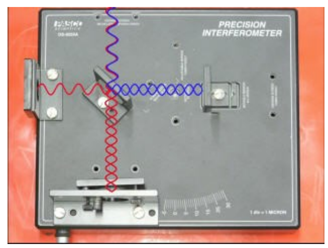




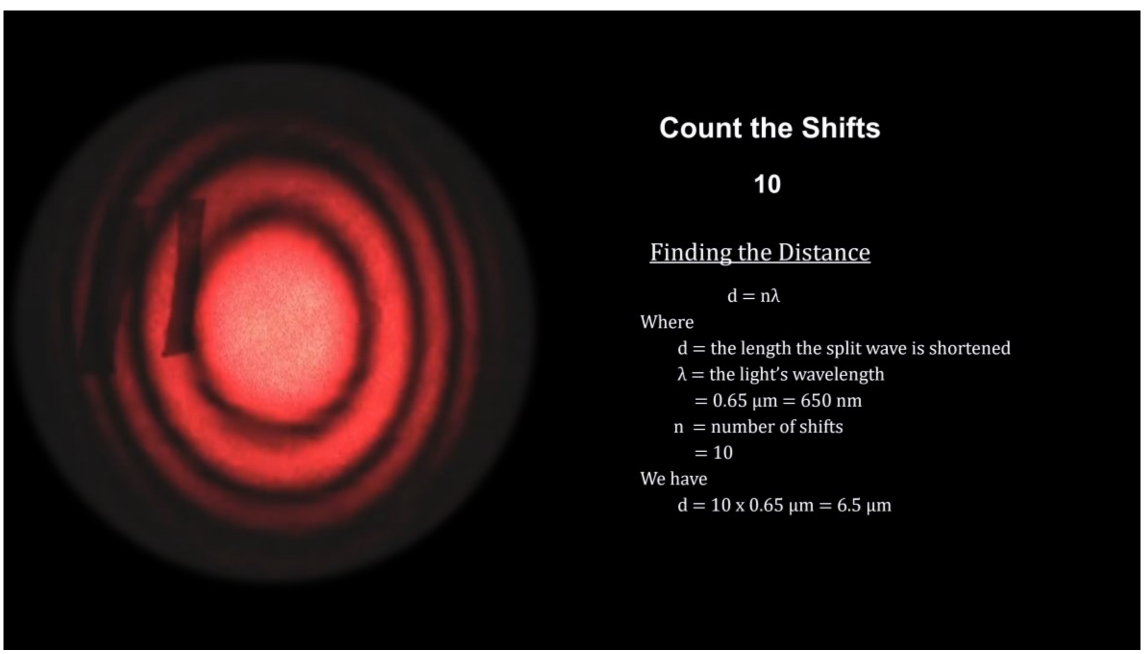
The main fringe has been marked with tape to help keep track of any shifting. If we move one of the mirrors by ¼ of a wavelength, that wave will have traveled ½ of a wavelength less distance than the other one. (It loses ¼ on the way to the mirror + ¼ on the way back.) This produces the maximum destructive interference. You can see the shift in the fringes from bright to dark.



As we continue to shorten the wave to the point that it travels one whole wavelength less than the other one, we return to being in synch and get back the maximum constructive interference. The fringe pattern has now shifted one full fringe producing a pattern just like the one we started with.

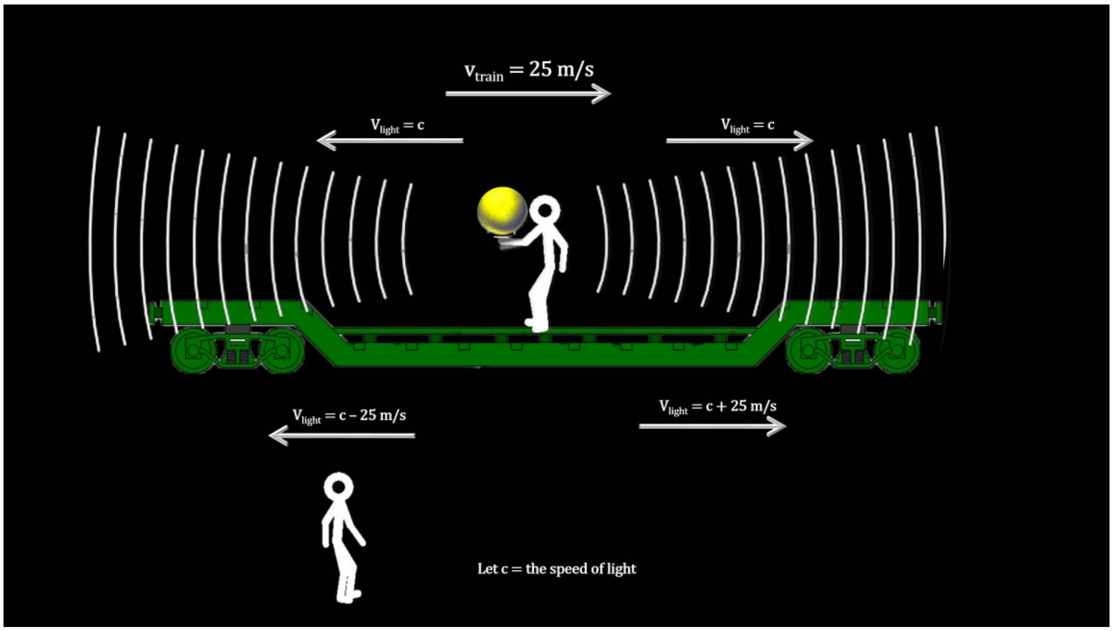


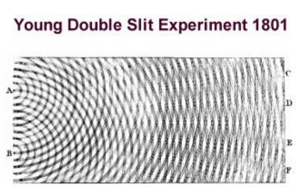
As we continue to shorten the path for the split wave, we can count the number of fringe shifts. In our experiment we used red light with a wavelength of 650 nm. Knowing the wavelength and counting the shifts gives us the distance. In this controlled experiment, each shift represents a distance of 650 nm. Shorter wavelengths will enable us to measure still smaller distances.



Michelson Morley Experiment

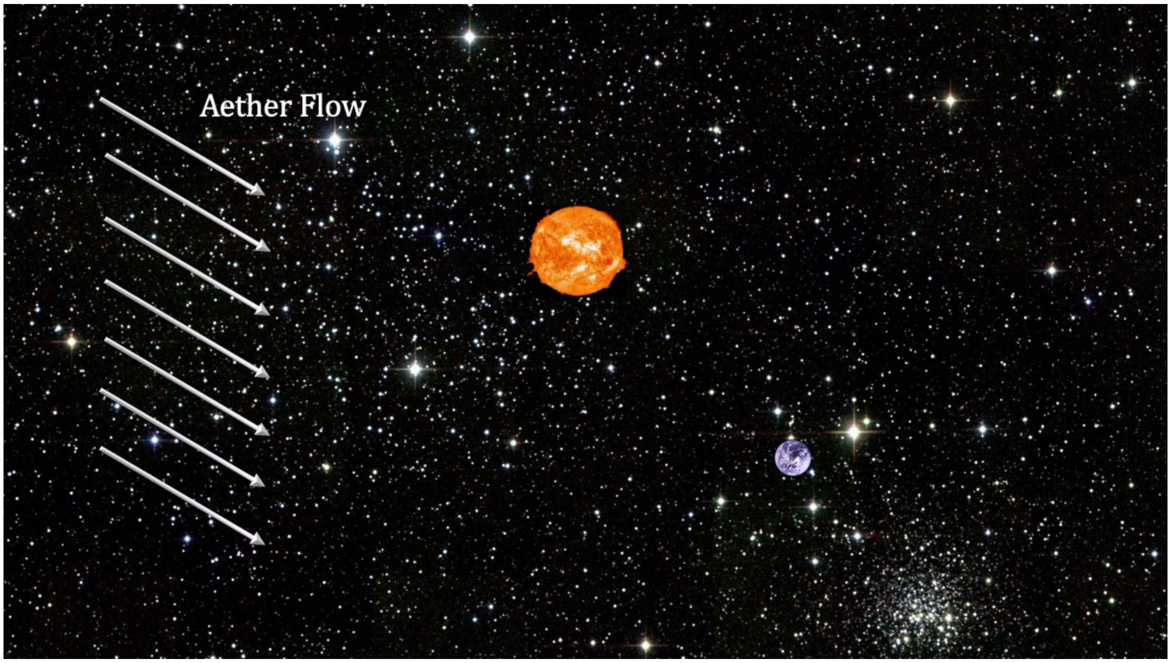
In 1887 Michelson teaming up with Edward Morley and published the results of their experiment that used an interferometer to measure the differences in the speed of light from platforms moving in motion with respect to each other. We'll spend a little time here going over how they did it.



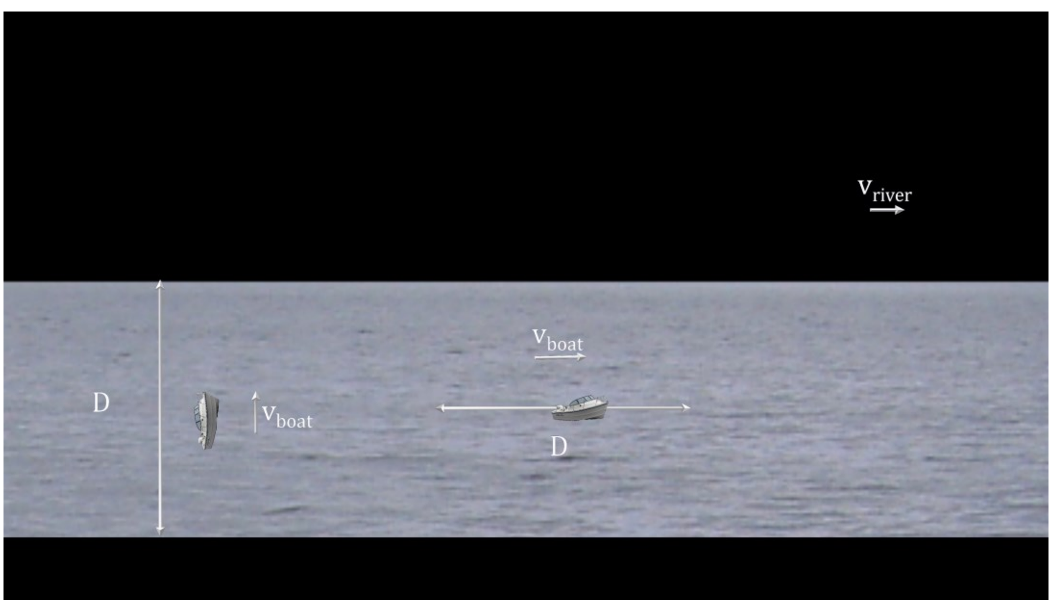


Since 1801 when Young proved that light traveled as a wave, and throughout most of the 19th century, it had been assumed that space was filled with a substance called the aether to support light propagation just like air supports sound wave propagation.

The aether represented the universal frame of reference against which all other motion could be measured. The question at the time was, how fast is the aether flowing. Or more precisely, how fast is the Earth moving through the aether. Michelson and Morley were trying to answer this question with their experiment.



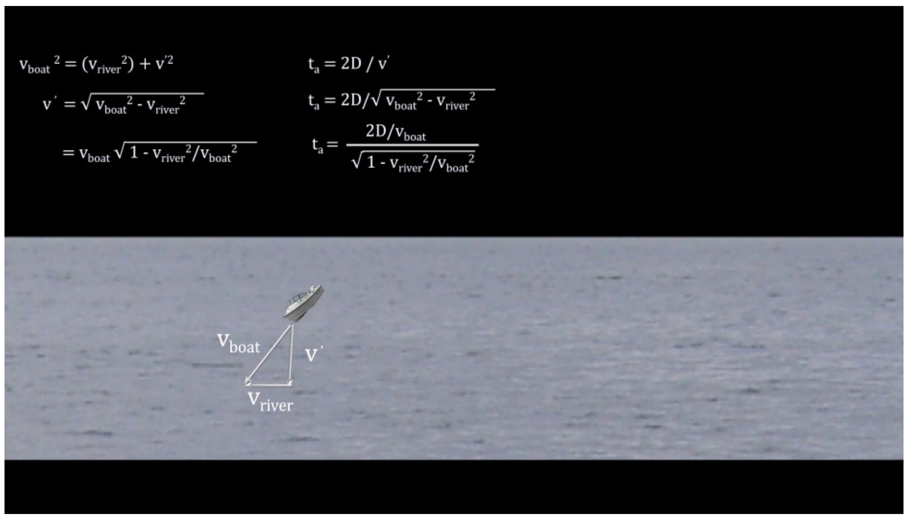
A good way to see what's happening is to picture a river that measures D across and is flowing to the right with speed v_{river}. Now we put two boats in the river, each moving with a speed v_{boat}. One boat will move across the river to a point on the other bank directly opposite the starting point and then return. The other boat will travel downstream the distance D and then return to its starting point. We'll calculate the time required for each round trip.



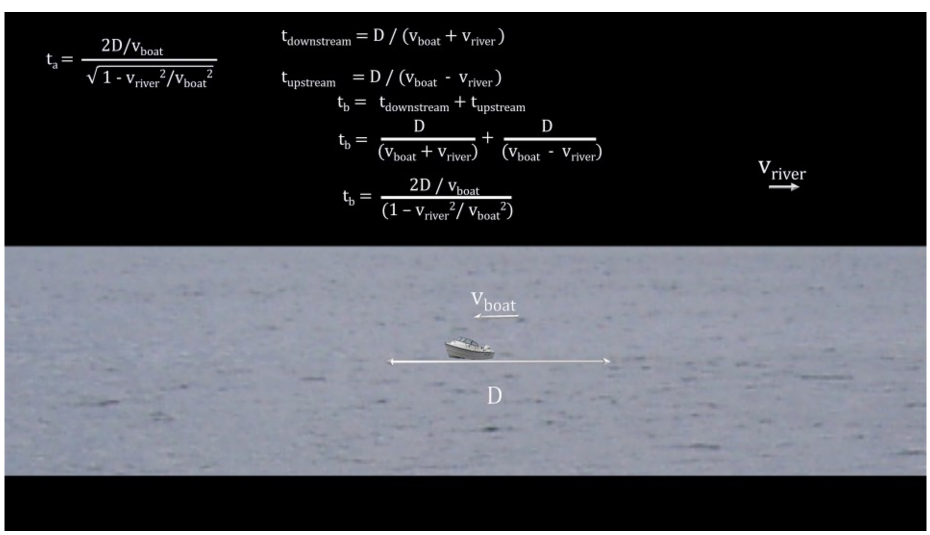
Let's take a look at the cross-river trip. If the boat headed directly for the destination point, the current would take it downstream and it would miss its target.

To compensate, the upstream component of its velocity would have to match the flow velocity of the river. This would give us a right triangle where v' would be the net speed across the river. We can calculate v' by using the Pythagorean Theorem.

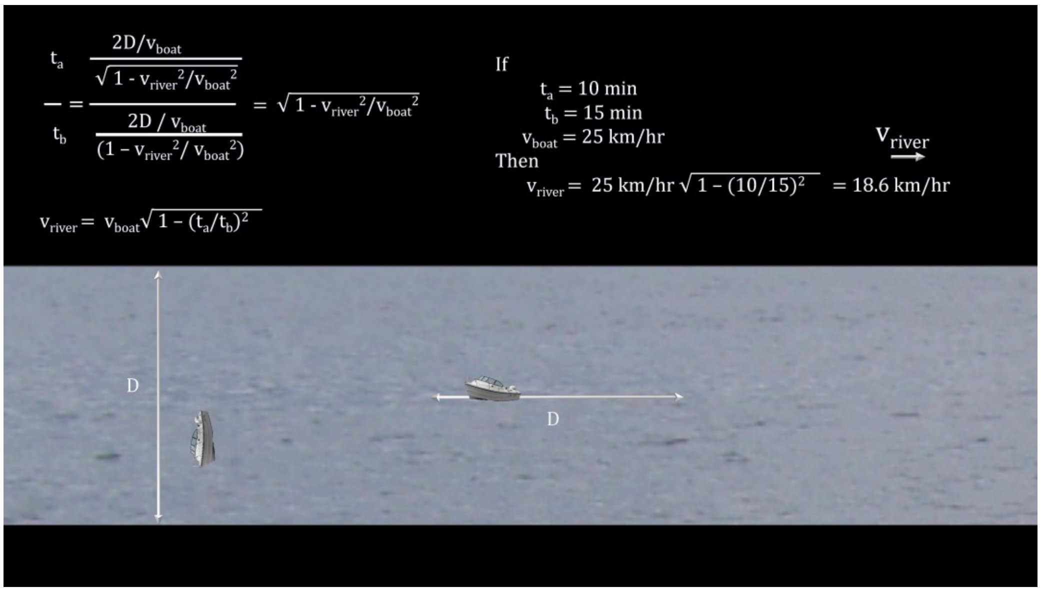
The same analysis works for the trip back, so the time for the round trip can be calculated as twice the time for one way. That's 2 times the distance divided by the v'. Substituting the value for v' we get the final equation.



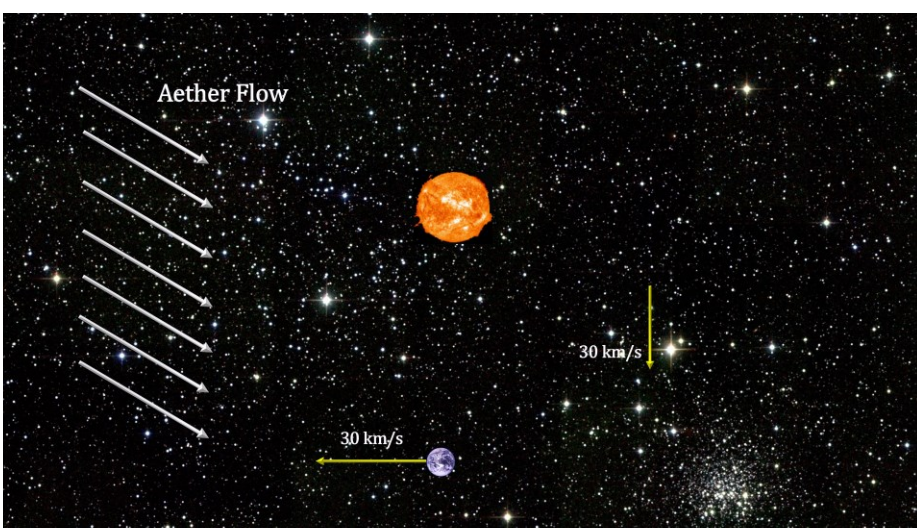
Now let's take a look at the boat traveling down the river and back. The time it takes to go the distance D is simply D dived by the speed of the boat plus the speed of the river. The trip back takes D divided by the speed of the boat minus the speed of the river. Using the common denominator to add these two times, gives the time it takes to make this round trip.



If we take a look at the ratio of the cross-river time t_a to the down-river time t_b, we see that it creates an equation that can be solved for the velocity of the river. For example, if the boat speed is 25 km/hr, and we carefully measure the time of the two trips to be 10 min for the cross-river round trip, and 15 minutes the down-river round trip, then we can find the river flow. In this example, it's 18.6 km/hr.

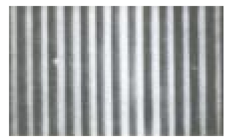


Michelson and Morley understood that the Earth is moving through the aether in different directions at different seasons. In our segment on the Solar System, we found that the Earth is revolving around the sun at 30 km/s. And depending where on the surface of the Earth you are, you could add or subtract as much as 1/2 km/s due to the Earth's rotational speed.

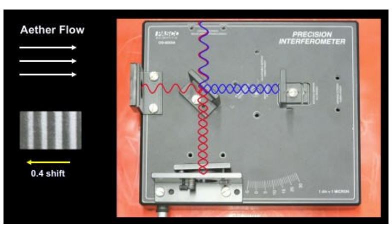


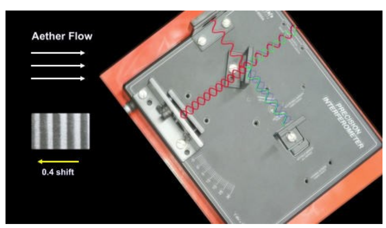
What Michelson and Morley did was to measure the ratios for light traveling with the aether and across the aether to determine the speed of the aether, just like we did for the boats in the river. Here's the apparatus that they used. It works like the one from MIT, only it's mounted on a stone slab and floating in a pool of mercury to allow for slowly rotating the interferometer.

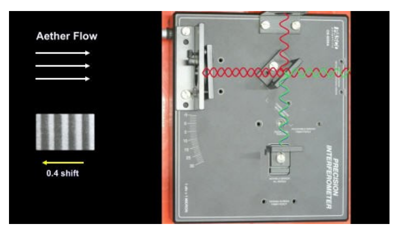
Here's the actual interference patter they saw.



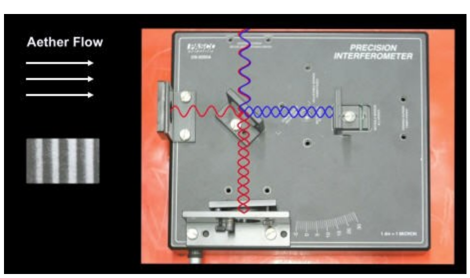
As the interferometer is rotated, the light flowing perpendicular to the direction of the aether would take time t_a, and the light flowing with and against the aether would take time t_b. Rotating the interferometer would change the ratio from t_a/t_b to t_b/t_a and the interference patter would shift. Using the speed of the Earth through the Aether, they estimated that the shift in the pattern would be just under ½ of a fringe.

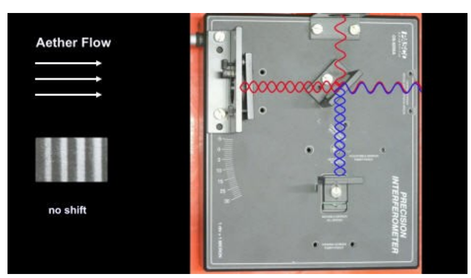






But there was no shift. When the experiment was performed at different seasons and at different locations, the results were the same. No shift.





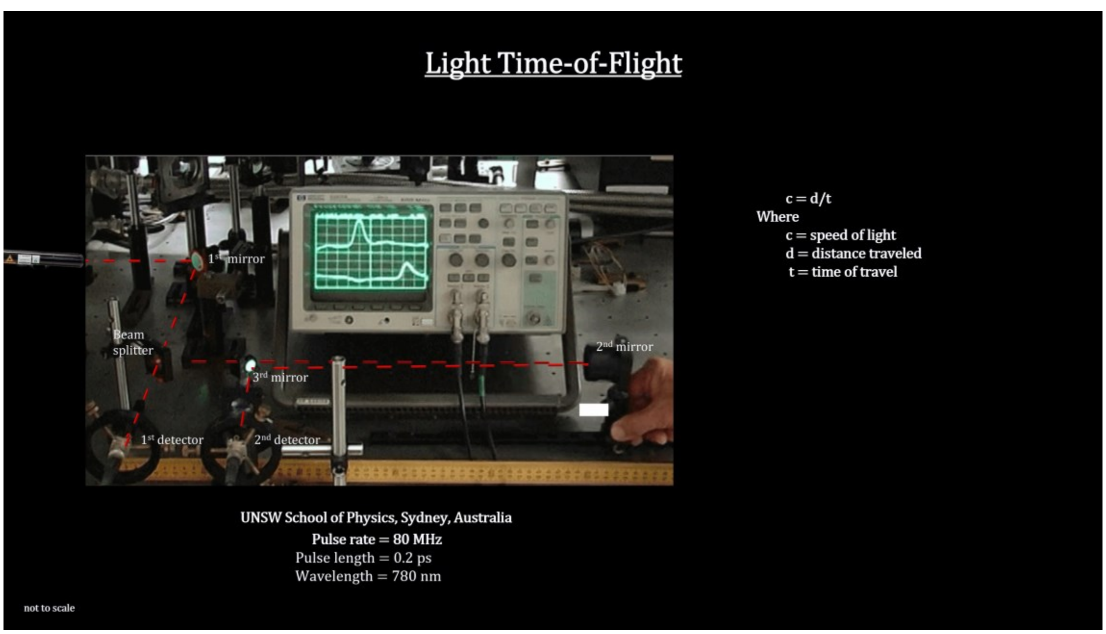
Initially, the fact that there was no shift was viewed as a failure by Michelson and Morley to measure the velocity of the aether. But on reflection, scientists started asking some very fundamental questions. Is there an aether? How can we add the velocity of light and the velocity of the platform and come out with the velocity of light? Are the Galilean transformations wrong? And for us, in this video book, a big question was 'does the fact that the speed of light is a constant mean that it is also a speed limit and nothing can go faster than that?' These are the questions we'll address with Einstein's special theory of relativity in our next segment.

Speed of Light – Time of Flight [Music: Chopin – Raindrops**]**

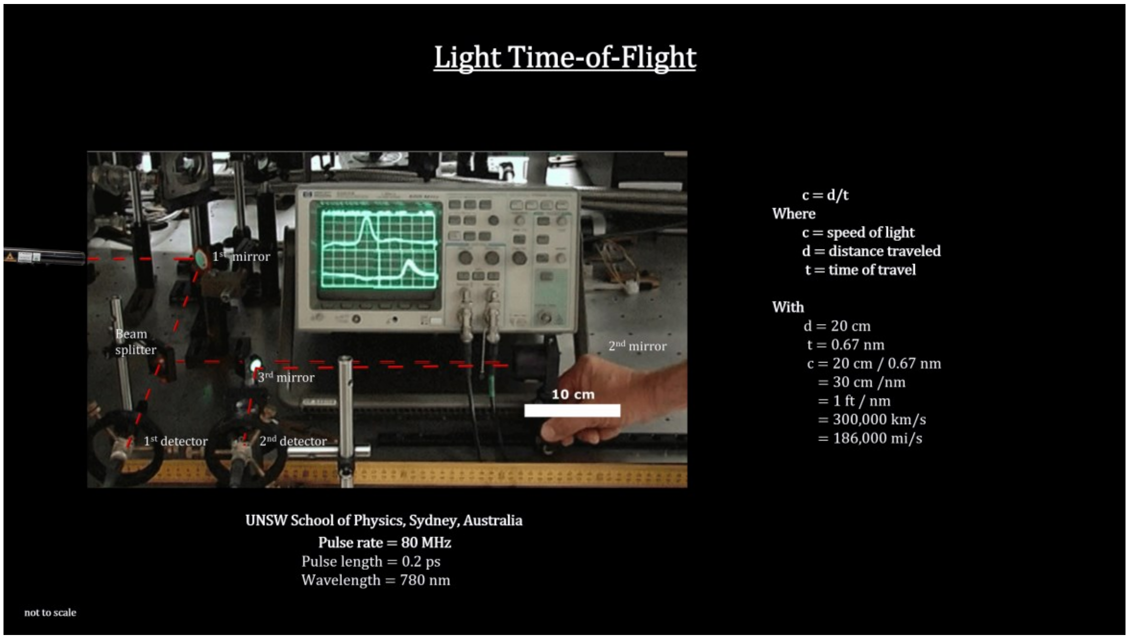
But first, we'll finish off this segment with a look at the two modern methods for measuring the speed of light. One method uses the time-of-flight like Fizeau and others did. Here's a typical lab experiment. This one is from UNSW School of Physics, Sydney, Australia. It uses a high-speed pulsed laser (off the screen), a beam splitter, mirrors, fast detectors and an oscilloscope.]

A high-speed pulsed laser produces a regular series of very short pulses. [The pulse rate is 80 MHz and each pulse has a length of 0.2 ps. The wavelength is 780 nm.] The red lines show the beam path. [They are not a photograph of the beam, of course: the air in the lab is clean so there is nothing to scatter the beam and so it is invisible from the side view.] The first mirror directs the beam to the beam splitter. The beam splitter directs half the beam to the first detector and the other half to the second and third mirrors before arriving at the second detector. Both detectors feed the oscilloscope. This instrument can record up to hundreds of millions of frames per second.

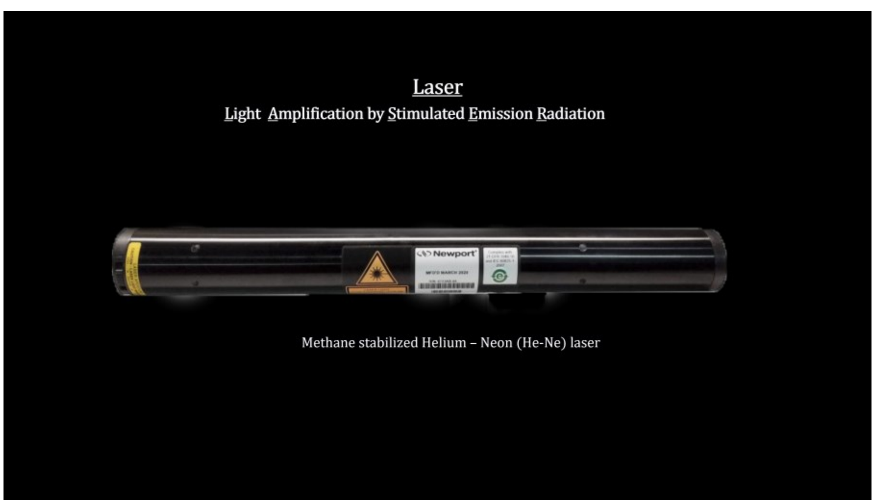
The screen of the oscilloscope shows the signal from the first detector on the top trace and that of the second detector on the lower. [The laser outputs a sustained series of pulses, and the signal from the first detector is used to trigger the oscilloscope trace for both channels.] The divisions on the horizontal axis are one nanosecond. The second pulse arrives several ns later than the first, because it has travelled a longer distance. [The shape of the pulses on the screen is largely the response of the detectors, rather than showing the time variation of intensity in the light pulse.]



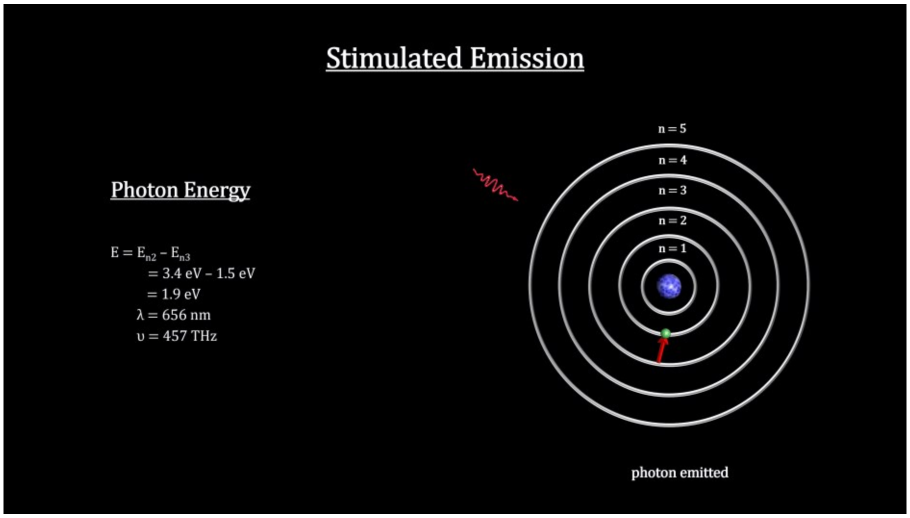
Now we move the second mirror 10 cm to the left. Because the beam has an out and back path, this reduces the path length by 20 cm. The pulse on the second trace arrives earlier by 0.67 ns, with respect to the first, giving us the value for the speed of light: c = 30 centimeters per nanosecond. That's 1 foot per nanosecond. In kilometers, that's 300,000 km.s^{-1} and in miles it's 186,000 miles per sec. This method for measuring the speed of light is good, but not good enough for the precision needed for such a key universal constant.



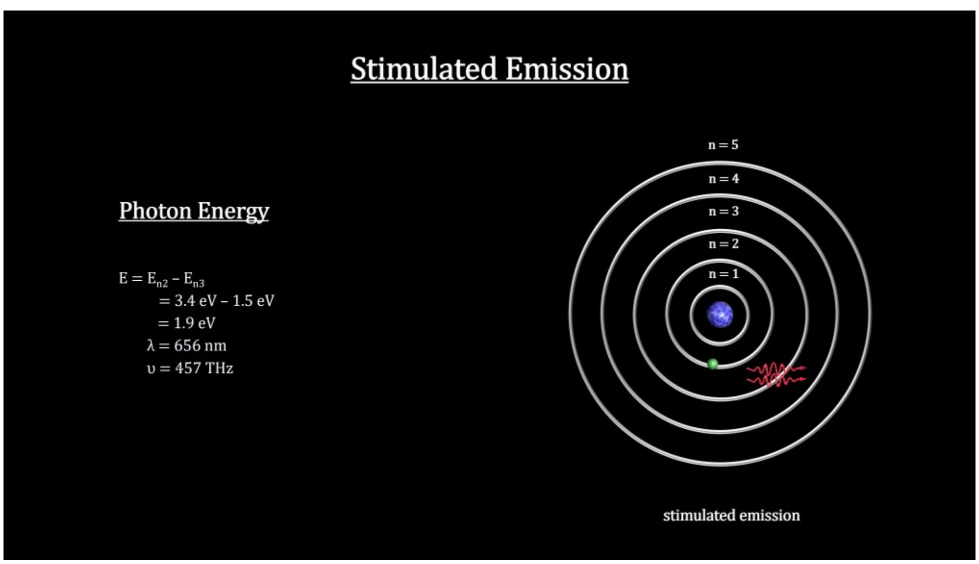
Given that speed of light in a vacuum will equal the light's frequency times its wavelength, all we need to do is to use a laser to create monochromatic light and measure its frequency and wavelength. To fully understand how this is done, we need to take a little deeper look at the laser that creates the light. The name "Laser" is an acronym for Light Amplification by Stimulated Emission of Radiation. The key is stimulated emission.



You may recall from the 'How Small Is It' segment on the atom, that electrons exist in discrete energy levels around the nucleus. When a photon with an energy E, hits an electron in a shell around a nucleus that has a higher shell it can reach with this same exact energy, the photon's entire energy is transferred to the electron instantaneously. This jumps the electron to a higher energy level. The photon is eliminated. When the electron drops from this excited state back to a lower energy level, a photon with the exact difference between energy levels is emitted in a random direction.

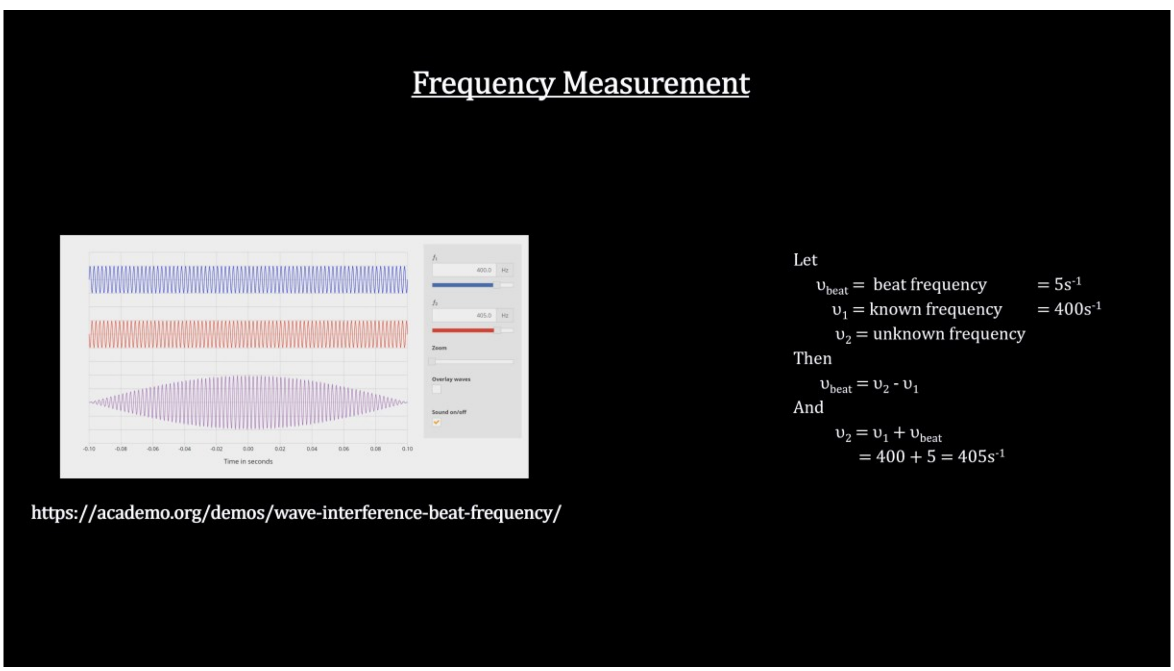


In 1916, Einstein theorized that a photon with its electromagnetic field and the right energy could stimulate an electron to drop to a lower energy level and emit a photon with the exact same energy, trajectory, polarization and phase as the incident photon. Where there was one photon, there are now two. They will travel off in random directions. Probabilities have it that every once in a while, a trajectory will be parallel to the tube they are in.

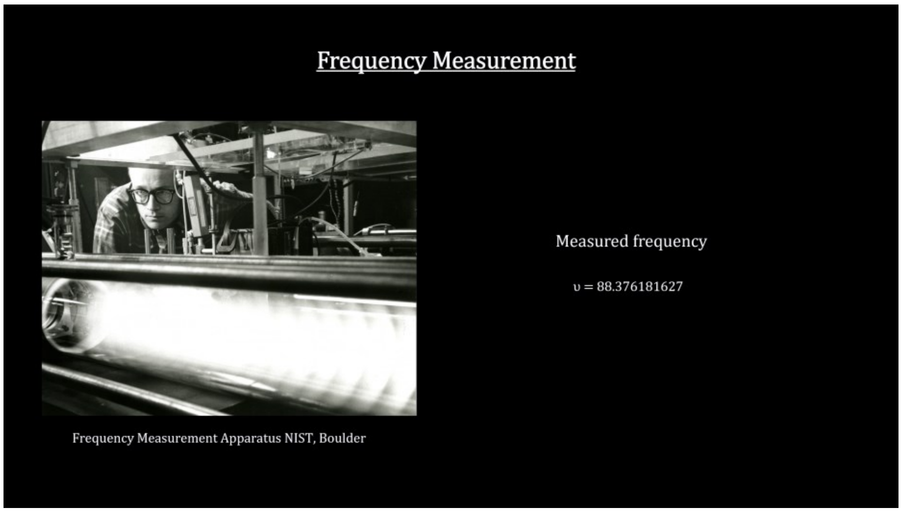


Lasers have one mirror that reflects 100% of the light that reaches it and the other reflects 99% and lets 1% through. So, these photons will travel to a mirror and be reflected. As they pass back through the tube, they will stimulate the production of additional duplicate photons as we just described for as long as the 'pump' keeps energizing electrons to higher energy levels. In short order, there will be trillions of identical photons leaving through the 99% mirror. This is the laser light. By the 1970s, the development of methane-stabilized helium-neon lasers with very high spectral stability and accurate cesium clocks made measurements to within an error of plus or minus 1 m/s possible.

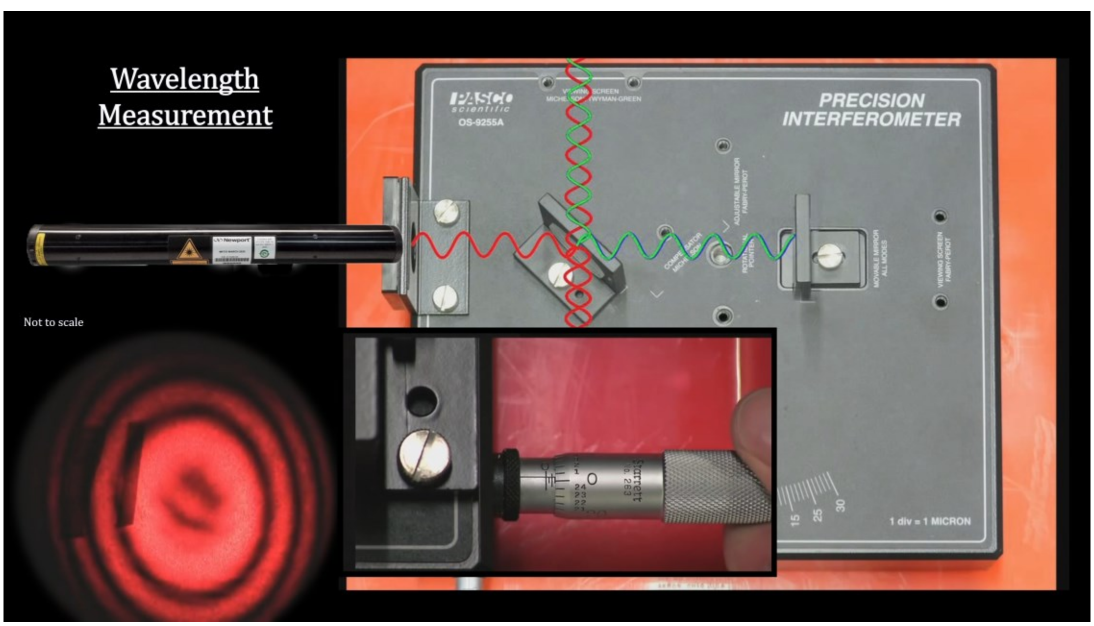
To measure the frequency, a technique called infrared frequency synthesis was used. It is the same idea we see with sound wave beats. We start with a known frequency, mix it with a higher unknow frequency and count the 'beats' created by the combination. Here we see a 400 cycles per second tone mixed with a higher frequency that produces a 5 cycles per second beat. This gives us the frequency of the second wave at 405 cycles per second. Using an iterative process, this can measure still higher sound frequencies.



For light frequencies, we use an oscillator with a known frequency and mix it with a higher frequency using a mixer diode to count the 'beats'. We iteratively get to the frequency of the laser light output. They found that the laser produces light with a frequency of 88.376181627 trillion cycles per second.



To measure the wavelength, we use an interferometer. First, we set up equal pathlengths for the light by getting the maximum constructive interference. Then we shorten one of the paths slowly to get 10,000 fringe shifts. The wavelength of the light is the distance that we had to use to get this many shifts divided by twice the number of fringe shifts. The results showed that the wavelength is 3.392231376 μm.



This measured wavelength along with the measured frequency gives us the speed of light at 299 792 456 m/s.

$$n\lambda = d/2$$
$$\lambda = d/2n$$

Where

λ = the light's wavelength

d = the length the split wave is shortened
= 67844.62752 µm

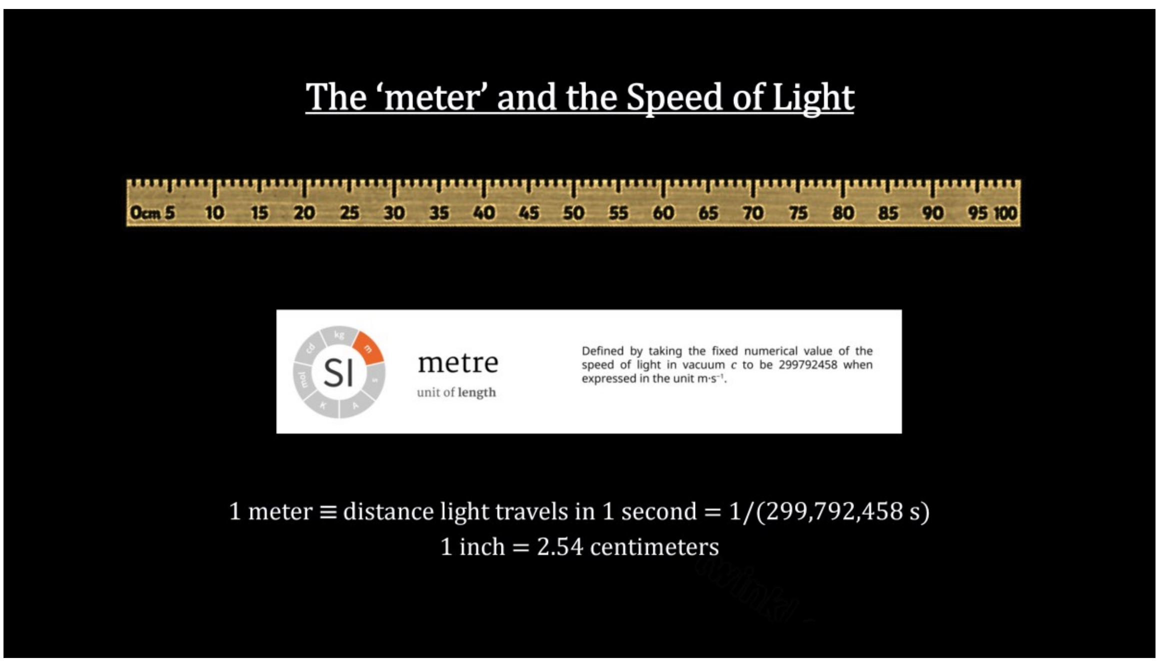
n = number of shifts
= 10,000

We have

$$\lambda = 67844.62752\ \mu m/2x10000$$
$$= 3.392231376\ \mu m$$

$$c = \lambda\upsilon = 299{,}792{,}458\ m/s$$
$$= 186{,}282.397\ mi/s$$

As of 1983, the speed of light in a vacuum is defined to have an exact fixed value when given in standard units. In fact, the meter has been defined by international agreement as the distance travelled by light in a vacuum during a time interval of 1/299,792,458 seconds. This makes the speed of light exactly 299,792,458 m/s. (Also, because the inch is now defined as 2.54 centimeters, the speed of light also has an exact value in imperial units.)



In the next segment on Special relativity, we'll cover why this value also represents the fastest anything can travel.

Music

@00:00 Giachino Rossini - William Tell Overture; London Philharmonia Orchestra; from the album The London Philharmonic Collection: Light Classics 2009

@00:49 Beethoven – Symphony No 7 Allegretto; Carlos Kleiber & Wiener Philharmoniker; from the album Beethoven: Symphonies Nos.5 & 7 1995

@12:08 Mozart – Violin Concerto No 5 Turkish II; Christian Altenburger, German; from the album 50 Must-Have Adagio Masterpieces 2013

@27:10 Joseph Haydn – Symphony No 98; Cappella Coloniensis; from the album 50 Must-Have Adagio Masterpieces 2013

@37:28 Chopin – Raindrops; from the album The Romantic World of Chopin's Piano, Vol. 3 2000

Greek letters:

- α β γ δ ε ζ η θ ι κ λ μ ν ξ ο π ρ σ τ υ φ χ ψ ω
- Α Β Γ Δ Ε Ζ Η Θ Ι Κ Λ Μ Ν Ξ Ο Π Ρ Σ Τ Υ Φ Χ Ψ Ω

⇒ → ± ⊙ ∞ ↛ ∃ ∄ ∈ ∉ ∬ ∫ ≅ ≥ ≤ ≈ ≠ ≡ √ ∛ ~ ∝ ℏ ÷ ∂ ⊥