Why we believe in Special Relativity: Experimental Support for Einstein's Theory

John S. Reid, Department of Physics, University of Aberdeen

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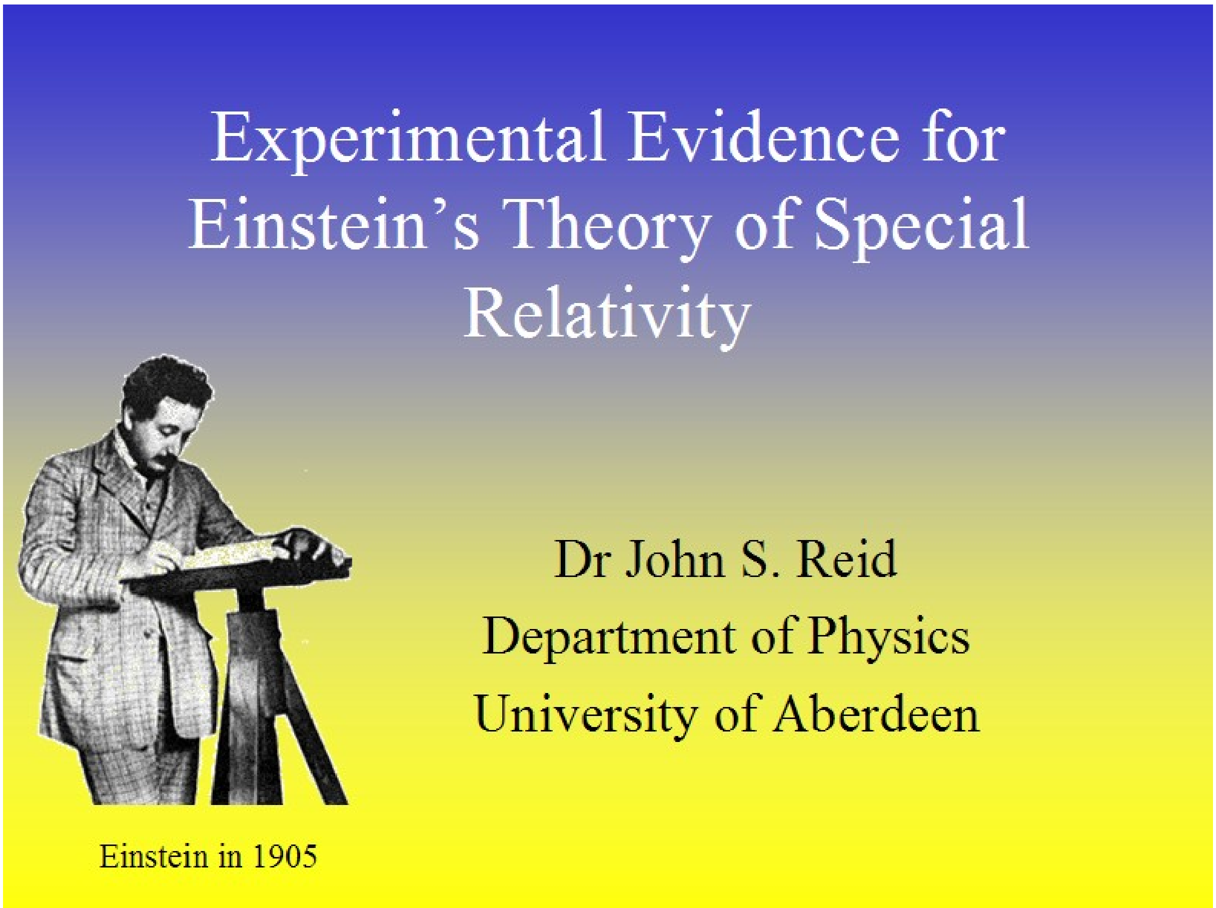
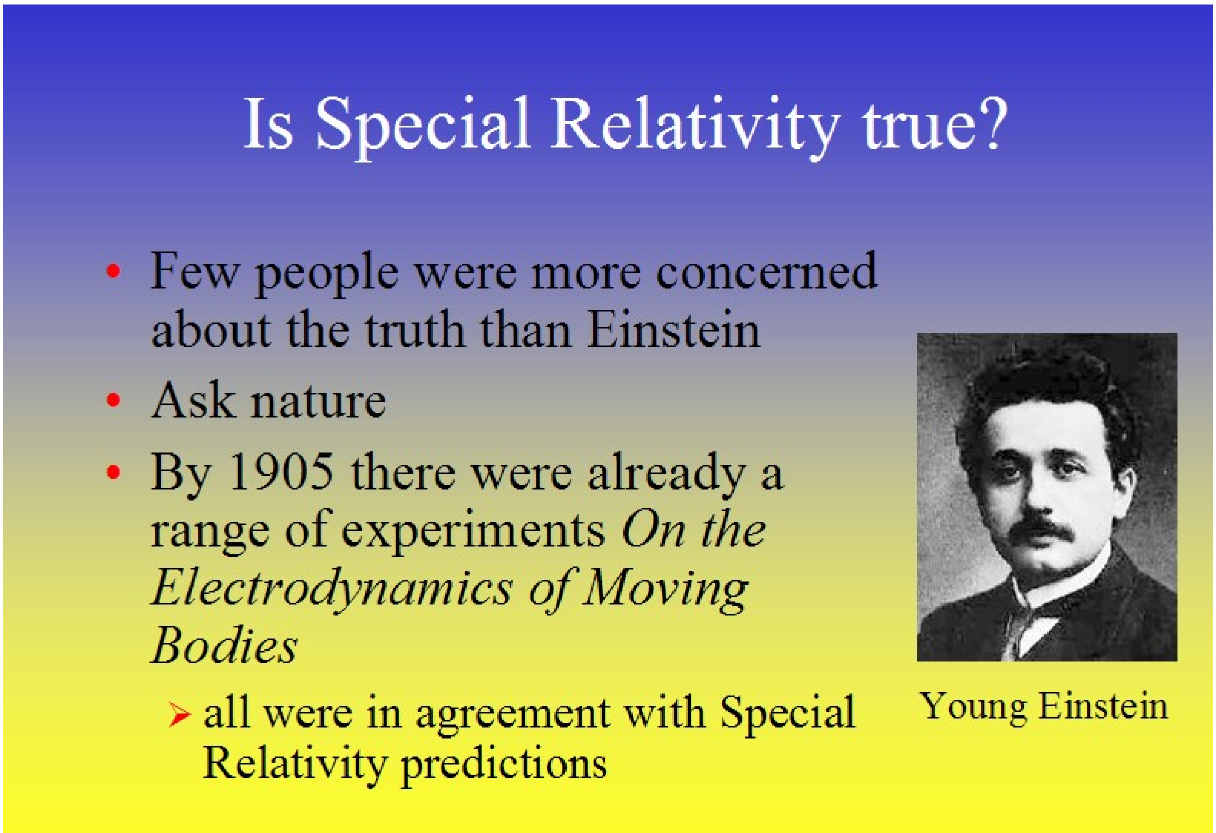
Einstein's Theory of Special relativity is sometimes presented as if it were a piece of philosophy or mathematics that arose purely from abstract thinking about space and time. This is not the case. Einstein based his theory firmly on experimental results known to him. Subsequently, the implications of his theory have been widely tested over the past century. No repeatable and generally accepted experiment has been found in disagreement with special relativity.

Title slide



Introduction

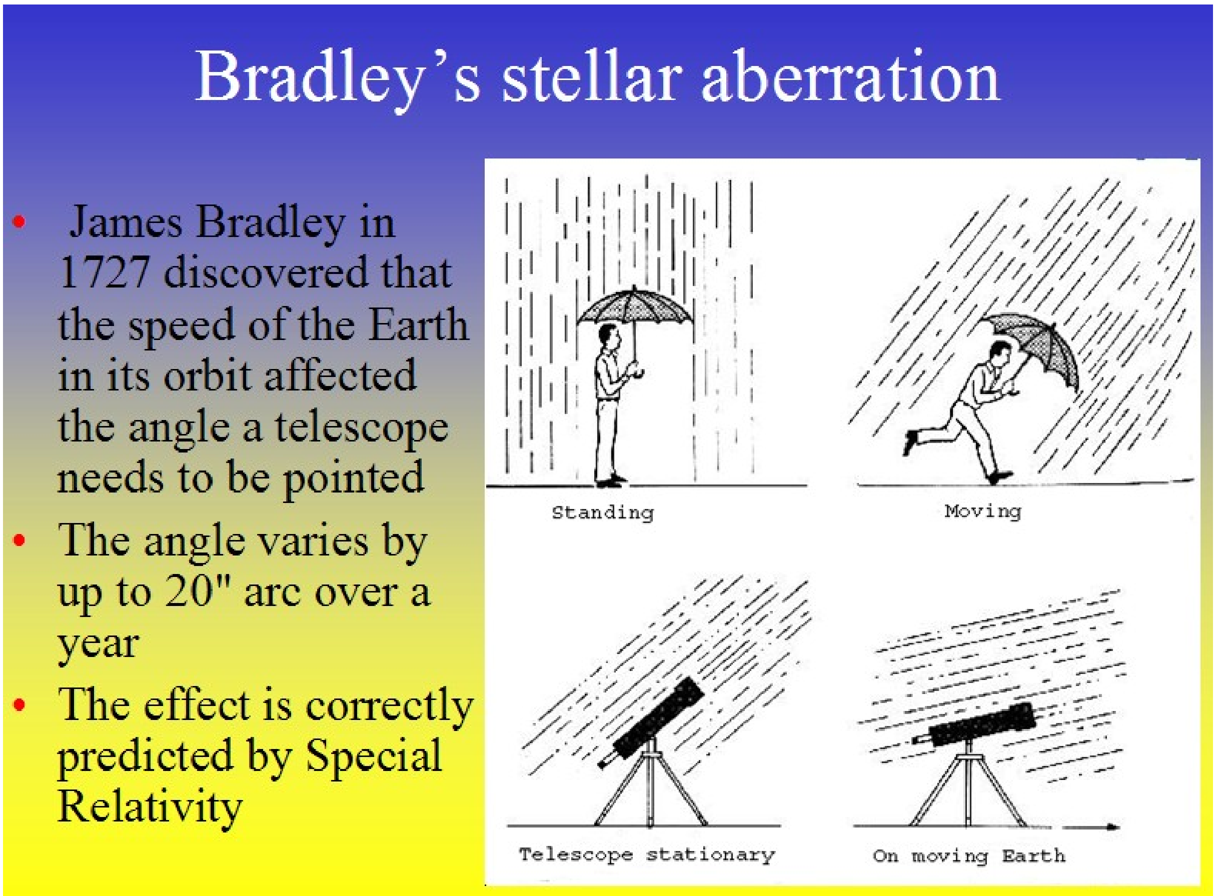
One of the influences that motivated Einstein throughout his life was a search for 'the truth'. It has been, and is, a motivation shared by many scientists and you can be sure that neither his contemporaries nor his successors would be prepared to sit back and accept such a radically new way of looking at nature as special relativity without asking 'is this really true?' It is one of the strengths of science that we don't ask questions like this of people but we ask nature herself. Einstein's original paper was '*On the Electrodynamics of Moving Bodies*' and by 1905 there were a range of relevant experimental results in this field, mainly optical results, that Einstein knew supported his theory.



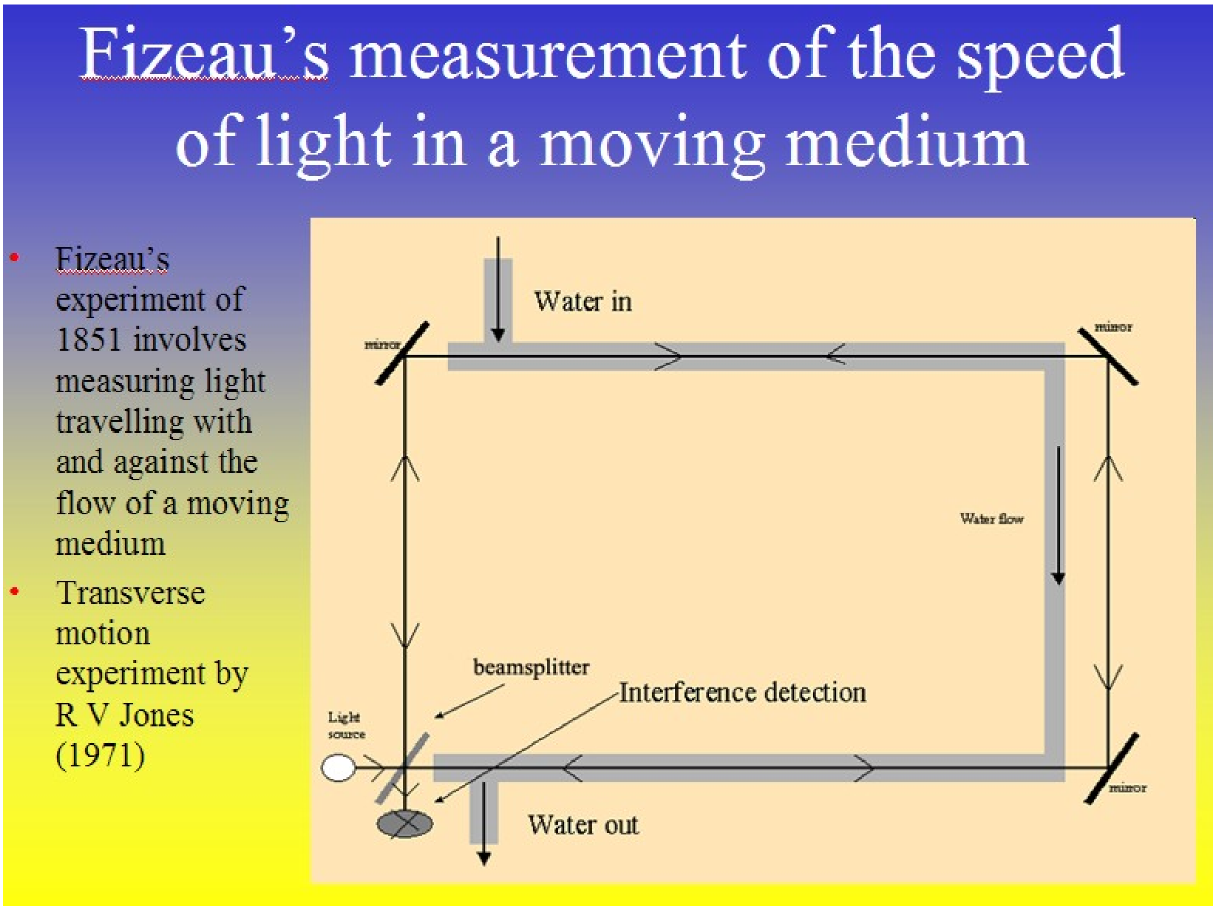
Pre 1905 results

I'll mention 3 of the pre 1905 results.

- **Bradley** in 1727 discovered that a small correction had to be made to the direction of a telescope aimed towards a star because of the motion of the telescope caused by the Earth orbiting the Sun. This phenomenon is known as 'stellar aberration' because if you don't make the correction the location of a star appears follows a small ellipse over a year. The result can have a diameter as great as 41 arc seconds; not much but measurable with care, even in 1727. Bradley's result is just what special relativity predicts. It is a more important result than you might suspect because it rules out one of the proposed 'fixes' to other testing experiments, namely that the special frame of reference referred to as the ether was always fixed with respect to the Earth. Bradley's result is not a definitive test but it is one relativity has to pass. **Airy** in 1871 tested whether the aberration remained the same if the telescope was filled with water, in which light travels more slowly. The result does and this is consistent with special relativity.



- **Fizeau,** who was the first to measure the speed of light by a laboratory technique also measured, in 1851, the effect of light travelling through a moving medium. The motion was in the same direction as the light travels. His result was predicted earlier by Fresnel and is just what Maxwell's electromagnetic equations and special relativity later predicted. Much more recently, there was some controversy over what happens when the medium is moving at right angles to the direction of travel of the light. The result was settled by an experiment carried out here in Aberdeen in 1971, with Prof **R.V. Jones** building the equipment and with Prof **Mike Player** covering the theory. The result vindicated the predictions of Maxwell's equations and the predictions of special relativity. You can see the apparatus they used on the bench here. Please examine it more closely after the lecture if you would like to. It is one of the modern items in our internationally important and wide-range collection of historic instruments of physics.



- Einstein has been criticised for not putting any references into his famous 1905 paper. Nevertheless, he was aware of the most significant result that supported his ideas, namely the null outcome of the **Michelson-Morley** experiment of 1887. I'll describe this in some more detail towards the end.

A table of results

In the century since Einstein's 1905 paper, a raft of tests have been carried out to check whether the background concepts upon which special relativity is based and its predictions are true. Only a few are shown on this table. Nature has replied through a megaphone: *yes*. I'll mention briefly or otherwise those in red.

I should say first that you will find a few papers in obscure journals and sometimes in the main journals reporting results that appear to be inconsistent with special relativity. Proponents supporting these results tend to be conspiracy theorists who accuse the scientific community of all being in cahoots to deny on principle anything that disagrees with special relativity. This of course isn't true. You will also find articles and even a few books around saying that relativity is wrong and the author has built a better mousetrap but they are pigeon-holed around the world under the heading of 'crank productions'. I certainly support the bottom line that no repeatable and generally accepted experimental result is in disagreement with special relativity.

A table of tests

Pre 1905 results		Optical experiments by Arago, Fizeau, Bradley, Airy with moving bodies
Tests of postulates	Round-trip tests of speed of light	Michelson-Morley experiment & derivatives
	One-way tests	lasers, masers and Mössbauer effect
	independence of speed of light	Alvager et al, Brecher (on motion of source),…. Schaefer (on energy)
	Limit on photon rest mass	Goldhaber & Nieto; Davis et al
	Tests on Lorentz invariance	Trouton-Noble experiment and others
Tests on time dilation, etc.	Particle lifetimes	muon lifetimes, Bailey et al
	Doppler formulae	Ives & Stillwell , McGowan et al
	Twin paradox	Hafele & Keating
Relativistic kinematics	limiting velocity is *c*	Brown et al, Glashow & Coleman, Stodolsky (neutrinos)
	variation of mass with velocity	Particle accelerators + special tests
	$E = mc^2$	Element transformations; astrophysics

For more see: http://math.ucr.edu/home/baez/physics/Relativity/SR/experiments.html

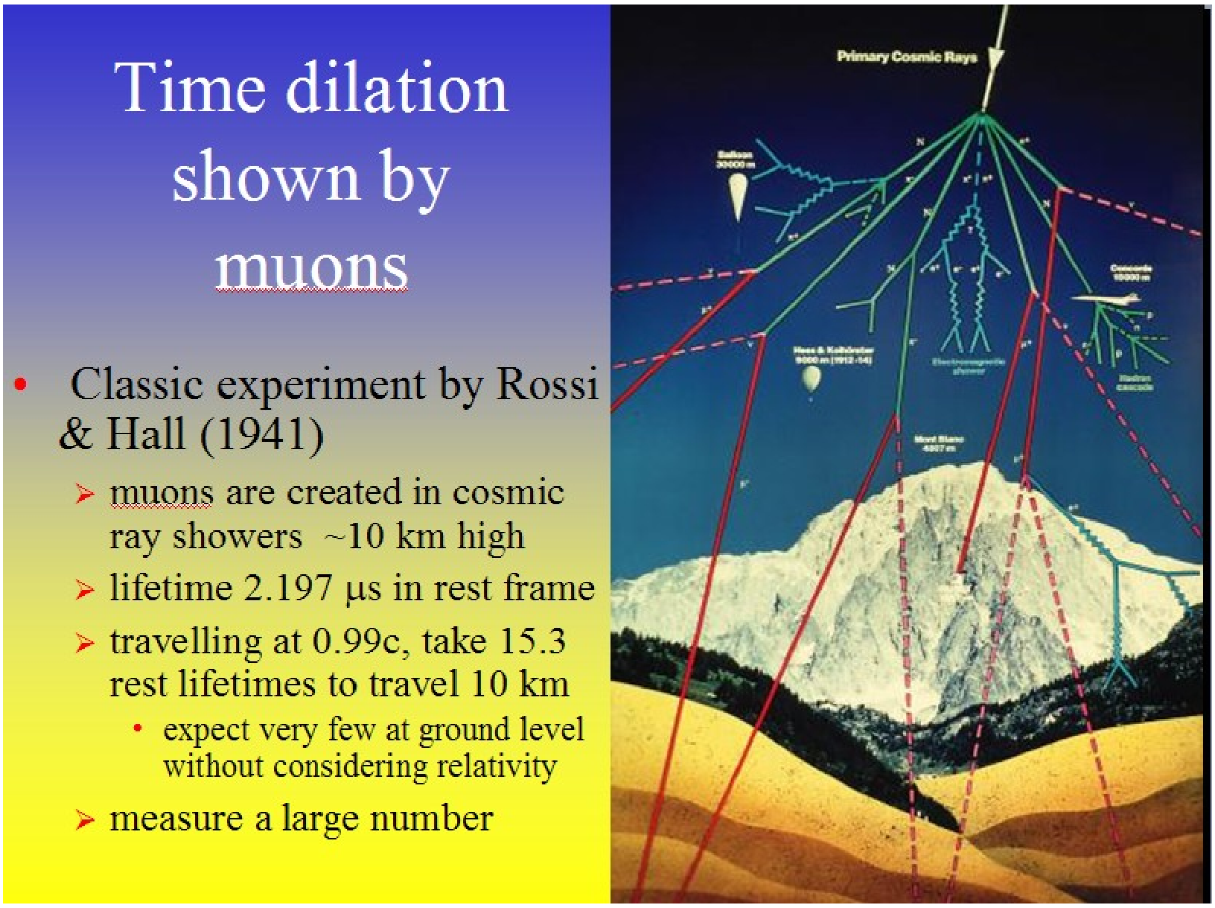
I'll outline a few of the experiments that have convinced me. We were quite pleased in experiments that we did at school or even as students in a University lab if we got the answer to a few percent. For some experimental tests, the agreement with the predictions of Special Relativity is much better than 1 part in a million million. If relativity is wrong, then you need to explain why all the experiments that agree with it give the results they do.

Time dilation

One of the most dramatic predictions of Special Relativity is time dilation. Time dilation implies that clocks in a frame moving with respect to you appear to run slow.

The muon experiment

Mu-mesons, or muons as they are called these days, are elementary particles bearing some similarity to massive electrons. They are created by collisions induced in particle accelerators and by the same process in cosmic ray showers when particles called π-mesons decay. The illustration shows muons in such a shower, shown in red, being among the particles that travel from several km high in the atmosphere to the surface of the earth. The fact that they reach the Earth at all is very curious indeed. But reach the earth they do, as you can hear in this radiation detector that records the natural background radiation in which life on earth evolves. About 1 in 8 of these clicks is caused by muons.



Muons have a short half-life of 2.197 μs before they spontaneously decay into an electron or positron and neutrinos. A bunch of muons travelling at 0.99 times the speed of light (0.99c) will only go 650 m before half of them have decayed. In the atmosphere, muons are created in a shower at a typical height of 10 km and will need 15.3 half-lives of time to reach the ground, more if they are coming at an angle. Lets suppose there are 15 rows in this lecture theatre and I were to give a sum of money to the back row and ask each row to take out half the money you get and pass the rest forward. How much would I have to give to the back row to ensure that I received at least 1 p at the front? The answer is about £327. After 15 rows each taking out half, very little of the original is left. The same should happen to the muons travelling earthwards. It doesn't, as this Geiger counter testifies.

Special Relativity explains why. For muons travelling at 0.99c, the time dilation factor is about 7. (γ = 7.09, to be exact). Their half-life observed in our ground frame of reference is longer by a factor of 7.09 and hence according to relativity the time needed for muons to reach the ground is not 15.3 half lives but only 15.3/7.09 = 2.18 half-lives. If there are only 2 rows dividing the £327 before I get it instead of 15, I'm not going to get just 1p but about £82, or 8,000 times as much.

Rossi & Hall experiment

Rossi & Hall

- Time to travel 2 km at 0.994c is 6.71 µs
- Half-life in moving frame is $\gamma \times$ 2.179 s = 19.92 s
- No. of half-lives to reach ground is 6.71/19.92 = 0.336

Courtesy: www.skypic.com/ nh/10-2362.jpg

	Relativity		Newtonian
	frame of muon	frame of ground	
Distance	0.219 km	2 km	2 km
Time	0.734 µs	6.71 µs	6.71 µs
Half-lives	0.337	0.337	3.08
Reduction	1.26	1.26	8.5

The original experiment was done by Rossi & Hall in 1941 who measured muon fluxes not 10 km high but at the top of Mt Washington in New England, about 2 km high, and at the base of the mountain. The effect is less for a height difference of only 2 km but for their muon speeds of 0.994c, slide shows that relativistically the reduction should have been only a factor of 1.26 whereas without time dilation the reduction would be a factor of 8.5. Rossi and Hall's figures were consistent with the relativitistic prediction. The experiment has since been repeated by others with convincing results.

In 1979 Bailey et al at a CERN accelerator reported a similar experiment with CERN generated muons of speeds 0.9994c, trapped in a particle accelerator, that were observed in the lab to have 29.3 times the muon rest lifetime, completely consistent with time dilation.

One of the consequential results in relativity is that no bodies can travel at a faster speed than the speed of light. Nobel prize winner Sheldon Glashow and collaborator Sidney Coleman showed in 1997 that the argument could be taken further. The mere existence of very high energy cosmic ray photons reaching the Earth is strong proof, without any extra experiment, of the existence of an upper limit of the speed of light c for material bodies. Their argument is that photons decay by pair production into electrons and positrons at a rate that can be calculated from particle physics. If the upper limit to the speed of electrons differed from c by a small amount, then high-energy photons (~20 Tev) would decay in nanoseconds and never travel any significant distance from their point of creation. The detection of these particles on Earth sets a tight bound of an upper limit to the speed of matter being within 1.5×10^{-15} of c.

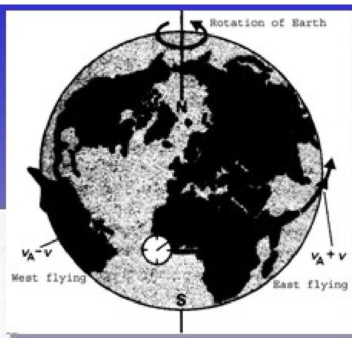
The twin paradox

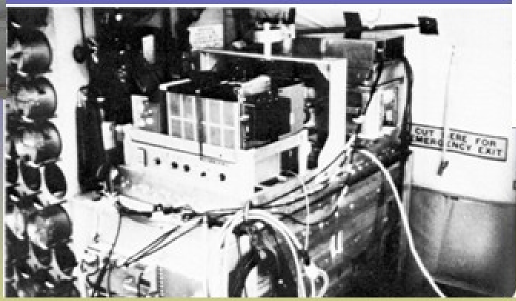
One implication of special relativity is the famous twin paradox in which one twin who travels away and returns finds the other twin who has remained behind has aged more than the travelling twin has.

The **Hafele and Keating Experiment** in 1971 described how 4 Caesium beam clocks, which are highly accurate clocks stable to about 1 part in 10^{13}, were sent on a global round trip on commercial airliners. The time these clocks gained or lost was compared with a master clock that stayed at the US Naval Observatory, who carried out the experiments. A difference in elapsed time measured by the moving clocks was expected both because of the time dilation of Special Relativity and because of a gravitational effect of General Relativity due to the difference in height of the surface clock and the aircraft clock of about 9 km. The time differences were nanoseconds, but Cs beam clocks can accurately measure such small differences.

The results are shown in the table on the slide for $T_A - T_S$, the difference in elapsed times for the aircraft clocks and the surface clocks. The Eastward flight took 41.2 hours, the Westward flight 48 hours. Because of the Earth’s rotation, the surface clock is moving and you can see that it is moving faster than the Eastward clock but slower than the westward clock. Hence, relative to the surface clock, the eastward clock runs slower, losing time, and the westward clock runs quicker.

Twin paradox





Predicted:	Time difference in ns	
	Eastward	Westward
Gravitational	144 ± 14	179 ± 18
Special Rel.	-184 ± 18	96 ± 10
Net effect	-40 ± 23	275 ± 21
Observed:	-59 ± 10	273 ± 21

- Hafele & Keating

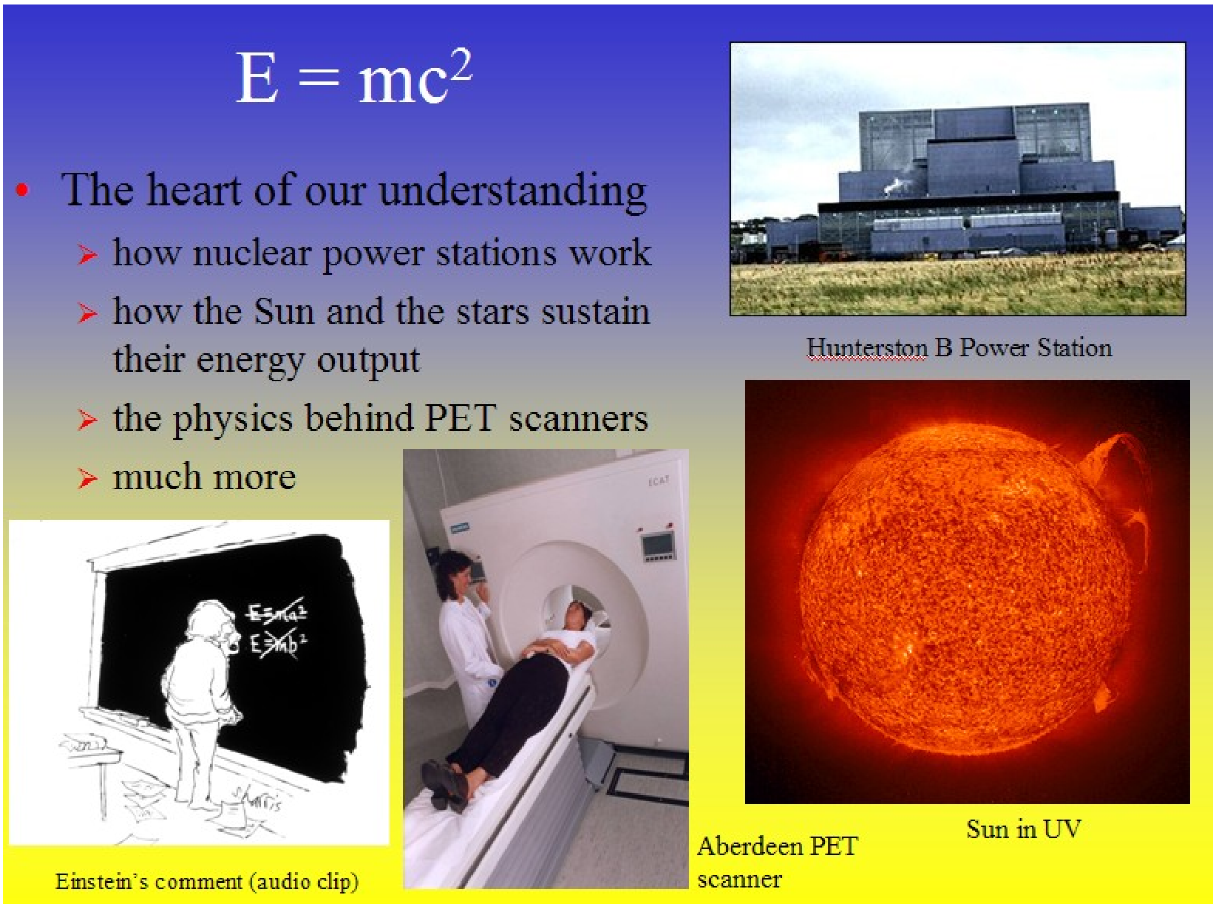
In this table, a positive time shift corresponds to aging faster, a negative number to aging slower.

The result was in complete agreement with Einstein's predictions. I'm sure the Navy weren't testing Einstein's theory just to show solidarity with modern physics. The GPS system was creation of the US military, based upon highly accurate clocks orbiting the world in satellites. Corrections have to be included for both Special Relativistic effects and for General Relativistic gravitational effects. Without these corrections the system would not produced the accuracy it does, by a long way. Light travels 1 m in about 3 ns so to get 1 m accuracy, and the military system can do better, the clocks and timing corrections need to be correct to this level of accuracy.

Would you bet your life on Special Relativity being true? Anyone who relies on GPS in bad weather, may be doing just that. Probably thousands of aircraft passengers and crew do so every day.

The Hafele and Keating experiment has been repeated on several occasions, flying clocks from London to Washington and back, and from London to Shanghai and back in recent versions. One resent trip was I believe sponsored by the international electronics firm Hewlett Packard. who make portable caesium clocks of considerably greater stability than those available to Hafele and Keating in 1971.

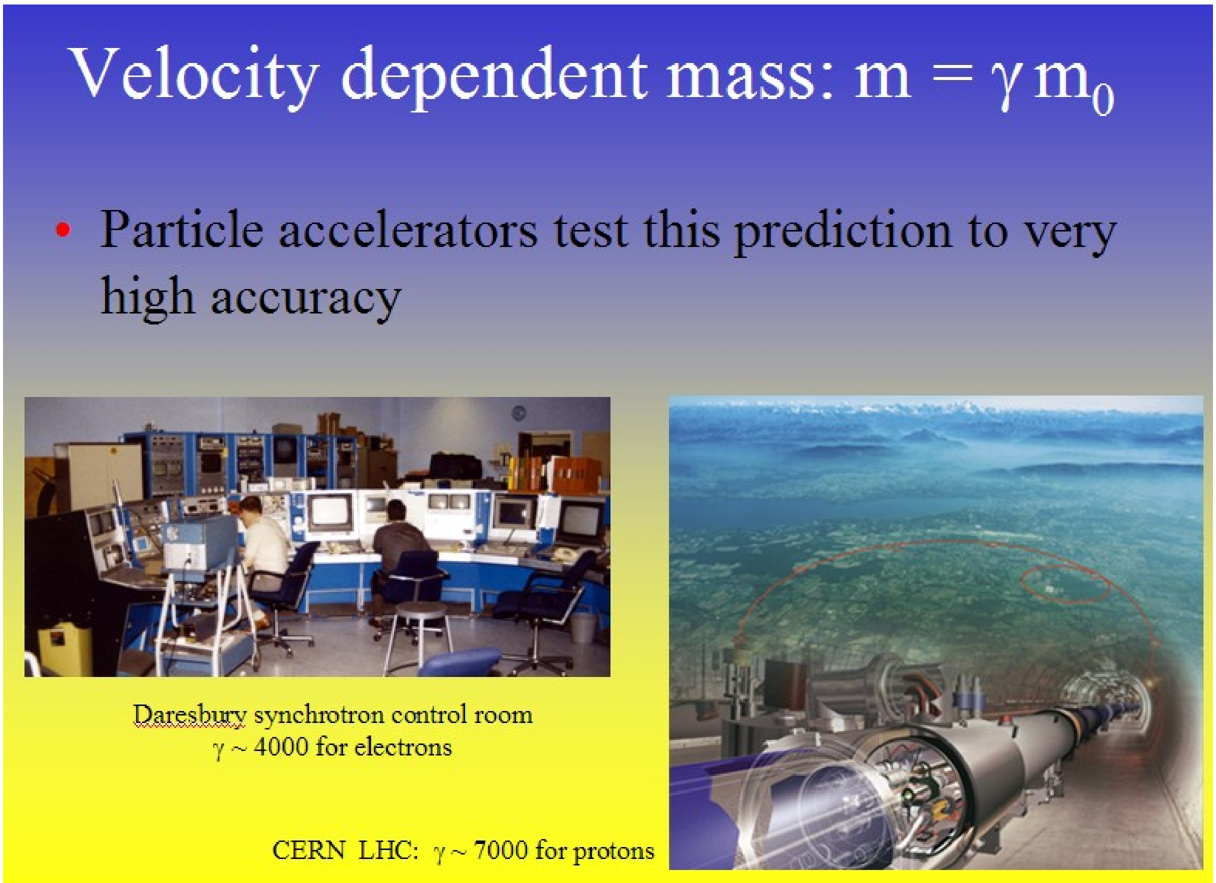
E = mc²



The inter-convertability of energy and mass is now part of the woodwork of modern physics, so much so that no-one is devising special tests to see if it is true. Commercial nuclear reactors work because of the mass loss when uranium fissions into lighter elements. The amount of energy produced is that expected from $E = mc^2$. I doubt if anyone weighs the products before and after to the nearest microgram. More quantitative is the so-called Standard Model of the Sun, which predicts how much energy is produced by fusion processes taking place within the Sun. This model has the reality check with the energy actually produced, the rate of consumption of the hydrogen from which the Sun is made, and so on. Much stronger, standard astrophysics explain how stars differing widely from the Sun evolve and has to be consistent with the population of stars actually observed. Even our local hospital PET scanner shows $E = mc^2$ in action when positrons emitted by the radio-isotope injected in to the patient decay into radiation when they meet an electron from a nearby atom.

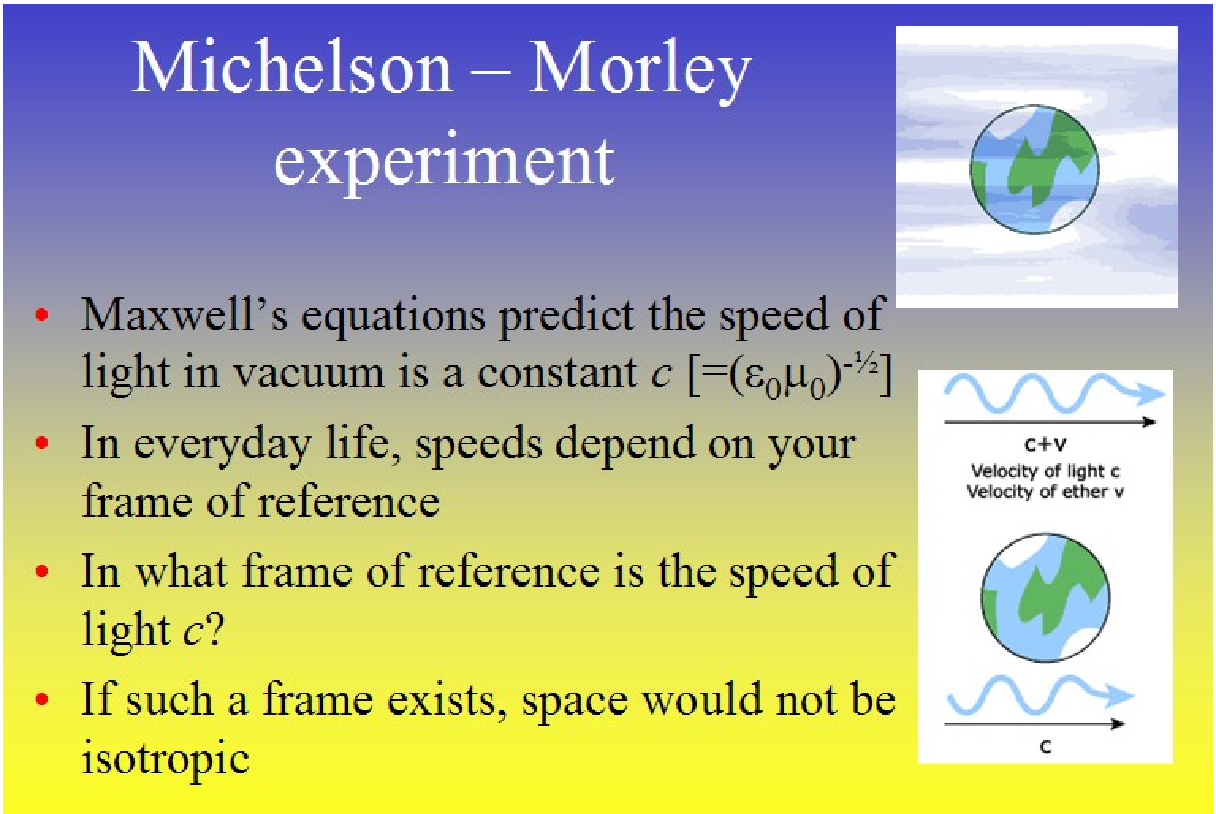
Einstein's own comments on the equation can be heard in the audio clip.

Velocity dependent mass: m = γ m_0



In my young days, which was well after 1905, we were taught about the conservation of mass. *Ex nihilo de nihil fecit*, "from nothing, nothing can be made" was the justification. Einstein didn't say that something could be created from nothing but he did say that the mass of an object depended on the speed it was travelling and hence the energy it had. He gave the precise dependence by the term called $\gamma = 1/(1\text{-}v^2/c^2)^{1/2}$ that keeps coming up in Special Relativity. This concept has been tested again and again in pretty well every particle accelerator that has been built. Particle accelerators are a multi-billion pound international industry these days. They are used for generating isotopes, such as the small cyclotron at Foresterhill, they are used to produce beams to create micron size features on the silicon chips of the electronics industry, they are used to provide a wide variety of X-ray, UV, and optical beamlines at research facilities such as the one at Daresbury in Cheshire, used by some of us academics at Aberdeen. The Daresbury facility accelerates electrons to an energy of 2 Gev. That is some 4000 times the electron rest mass and implies that relativistic electrons have 4000 times their normal mass. Accelerators are designed and built to exquisite tolerances based upon special relativity. They need to be. If the mass effect were not taken precisely into account in the roughly circular accelerator then the beam would very quickly crash in to the wall of the accelerator. To keep the beam circulating for hours, which is what happens, you need to know very precisely its mass. Einstein relationship is what is needed and it works precisely. CERN's LHC accelerator, due to come on line in 2007, will accelerate protons to 7 TeV, giving them about 7000 times their rest mass.

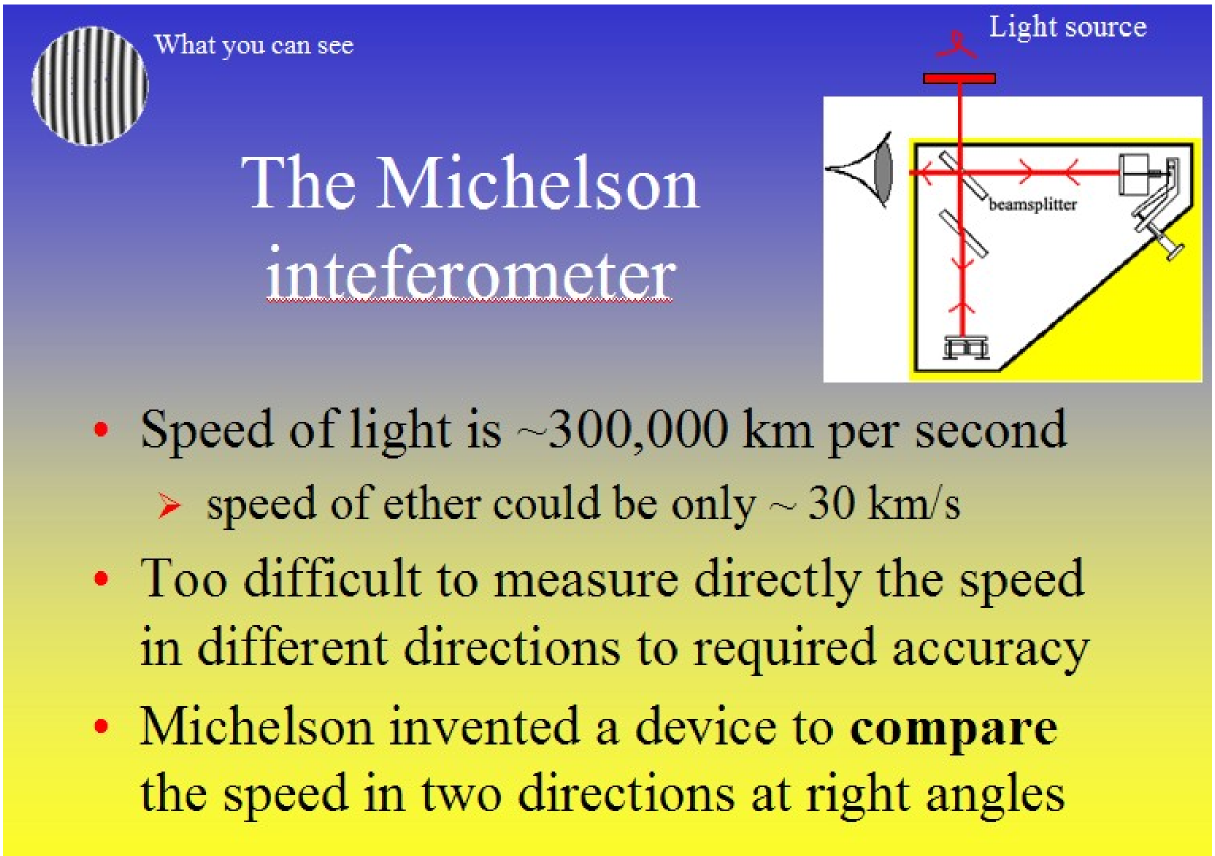
Michelson – Morley experiment



When James Clerk Maxwell predicted the existence of electromagnetic waves there was an extraordinary feature of his prediction whose full implication wasn't fully appreciated at the time. Maxwell's equations included a fixed constant $c = (\varepsilon_0\mu_0)^{-1/2}$ for the speed of the electromagnetic waves, the speed of light. In everyday life, speeds aren't fixed constants. They depend on how you, the observer, is moving. Imagine you are the police standing on the roadside clocking my car coming towards you at 60 mph. Alternatively, imagine in a second scenario that you are in a police car coming towards me in my vehicle at 60 mph. You would expect your radar gun now to read the closing speed between us of 120 mph. There isn't one constant that describes my speed. Maxwell's speed of light must therefore be the speed in one particular frame of reference, which contemporary physicists called *the ether*. Special relativity is based on denying the existence of such a special frame and saying that there is no a unique frame of reference in which the velocity of light in vacuum has Maxwell's value. Hence a test of relativity is to suppose that there is such a frame moving at velocity v relative to the apparatus. The task is to measure v.

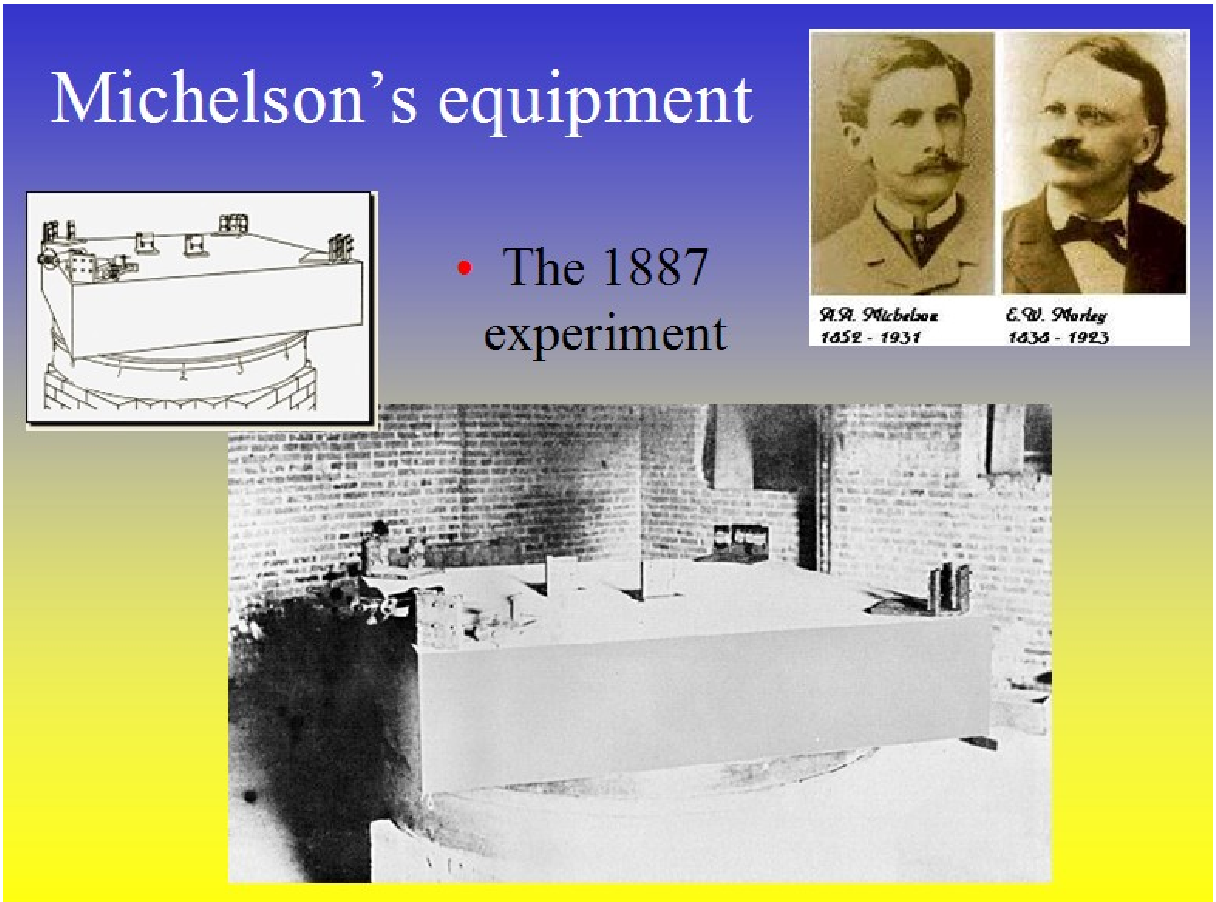
A century of experiments have tried to measure *v*. Einstein was aware of the result of the first and most famous of these, the Michelson-Morley experiment, and was aware that this experiment found *v* was zero within experimental error. The Michelson-Morley experiment underpins a central assumption in relativity. It is one of the classic experiments of physics.

The Michelson interferometer



Michelson hit upon an ingenious way of measuring the speed of the invisible ether. His problem was that the speed of light is about 300,000 km s^{-1} and whatever our speed was relative to the invisible ether it should be at least 30 km s^{-1}, due to the orbital speed of the Earth around the Sun, as Bradley had demonstrated. To detect this Michelson needed to measure the speed of light to an accuracy of about 10 km s^{-1}. This accuracy was beyond the scope of technology in the 1880s, when he was considering the issue. Michelson was the best optical experimenter of his generation. He had a stroke of genius. He realised that he just needed to measure the difference in the speed of light in the direction of the ether and at right angles to the ether. This could be done by a 'round trip' experiment in a device with two light paths at right angles to each other. He invented such a device, now called a Michelson interferometer. I have one here. It turns out to be an enormously versatile instrument with a huge number of uses.

Michelson's equipment



The bottom line of the experiment is to rotate the equipment smoothly round and if the speed of light is different in different directions the comparison times between light travelling along the two arms will change. Comparison fringes seen in the equipment will shift with the rotation. Michelson found no shift at all. You can see these fringes if you look in to the equipment afterwards. The limit on his sensitivity was ~15 km per second.

The result

The result was that no velocity could be found. The experiment has been repeated on many occasions with variant and improved equipment. It is not that easy an experiment to do. The strong consensus of results is that no ether can be detected.

The result

- There is no special frame of reference where the speed of light is *c*
- The experiment has been repeated many times in many different variants
  - one such variant by Brillet and Hall in 1979 using lasers reduced the limit of any difference in light speed in different directions to < 30 m/s

Conclusion

Theory		Light propagation experiments							Experiments from other fields					
		Aberration	Fizeau convection coefficient	Michelson-Morley	Kennedy-Thorndike	Moving sources and mirrors	De Sitter spectroscopic binaries	Michelson-Morley, using sunlight	Variation of mass with velocity	General mass-energy equivalence	Radiation from moving charges	Meson decay at high velocity	Trouton-Noble	Unipolar induction, using permanent magnet
Ether theories	Stationary ether, no contraction	A	A	D ✗	D ✗	A	A	D ✗	D ✗	N	A	N	D ✗	D ✗
	Stationary ether, Lorentz contraction	A	A	A	D ✗	A	A	A	A	N	A	N	A	D ✗
	Ether attached to ponderable bodies	D ✗	D ✗	A	A	A	A	A	D ✗	N	N	N	A	N
Emission theories	Original source	A	A	A	A	A	D ✗	D ✗	N	N	D ✗	N	N	N
	Ballistic	A	N	A	A	D ✗	D ✗	D ✗	N	N	D ✗	N	N	N
	New source	A	N	A	A	D ✗	D ✗	A	N	N	D ✗	N	N	N
Special theory of relativity		A	A	A	A	A	A	A	A	A	A	A	A	A

Legend: A, the theory agrees with experimental results.
D, the theory disagrees with experimental results.
N, the theory is not applicable to the experiment.

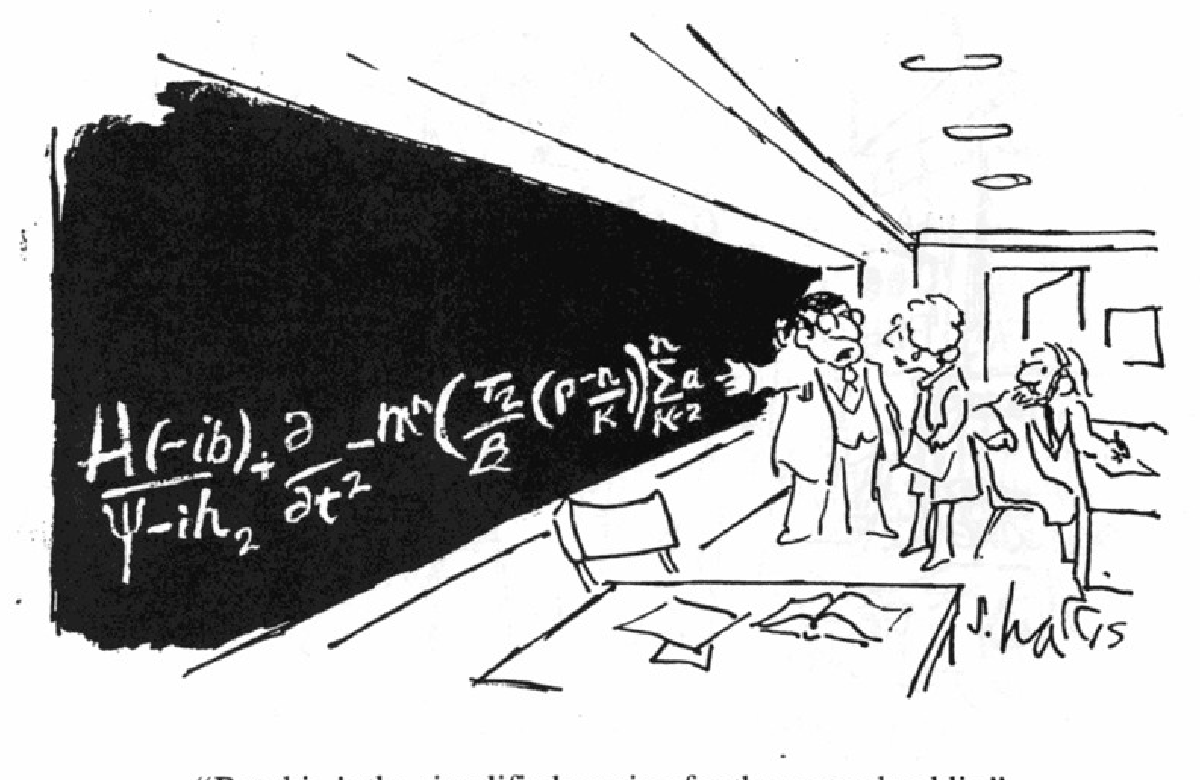
Alternative ideas versus Special Relativity

Einstein in 1920

I'm showing as a final slide a table that made an impression on me when I first saw it many years ago. It lists 13 key experiments that have a testing relevance to Special Relativity in the columns, and the predictions of 6 alternative theories to Special Relativity in the rows. The red crosses mark the places where the experimental results disagree with the predictions of the theory. Only Special Relativity is in agreement with all testing experiments.

Special Relativity is built into the woodwork of modern physics. Its results are used all the time and areas of physics that use these results work very well. Although some of the results of Special Relativity are counter-intuitive, in hindsight what Einstein did now seems natural. He realised that the incompatibility between Newtonian Mechanics and Electricity & Magnetism should and could be resolved by re-writing the old mechanics and not the new Electricity & Magnetism. In the past this re-write has seemed a bit like a princess climbing into the bed of an elephant and saying "this bed isn't right for the both of us. You'll have to move". Einstein successfully moved the elephant and 100 years of subsequent experiment has proved it was the right thing to do.

JSR



"But this *is* the simplified version for the general public."

Courtesy Philip Harris