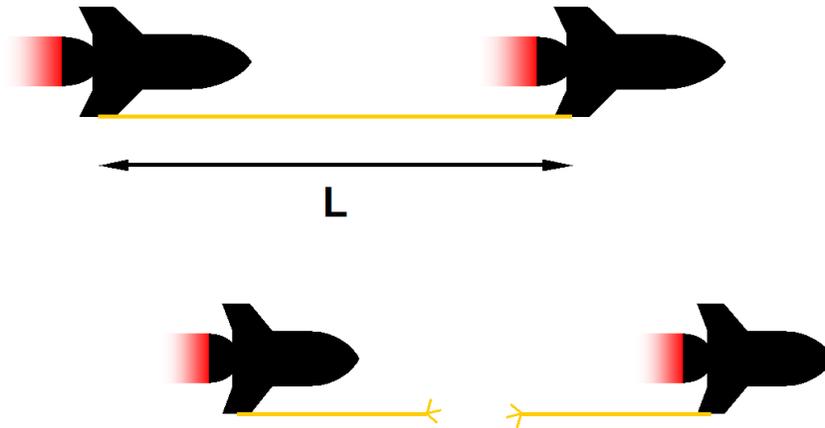


Bell's spaceship paradox



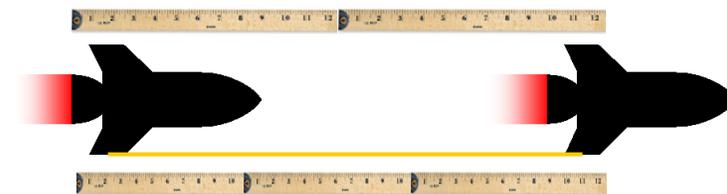
If the two ships start accelerating at the same time,
I always see them travelling at the same velocity,
and keeping a constant distance...
But I said the objects get shorter when they're moving;
is the rope now too short? **Does the rope break?**

mardi 30 octobre 12

1

If their rulers get shorter,
then anything which looks the same to us
is actually getting longer (to them)...

A meterstick carried on the ship looks shorter to us, but the
distance between the two ships looks the same.



There is no escaping the conclusion: it would take someone in the
ships' reference frame more meter sticks to span the distance.
**Unless the rope gets longer in the ships' frame, it must break
(or pull the ships closer together).**

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2

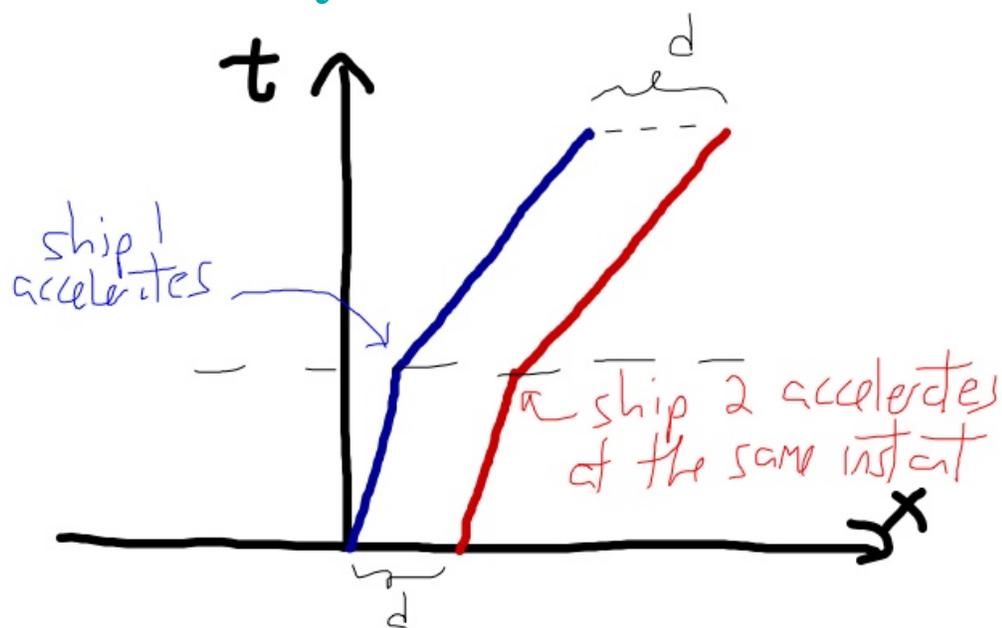
How would someone on one of the ships describe the physical cause of the rope breaking???

If the rope has a fixed length and breaks, it must be because the ships get further apart – but why should they get further apart if they are accelerating at the same rate relative to the Earth?

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3

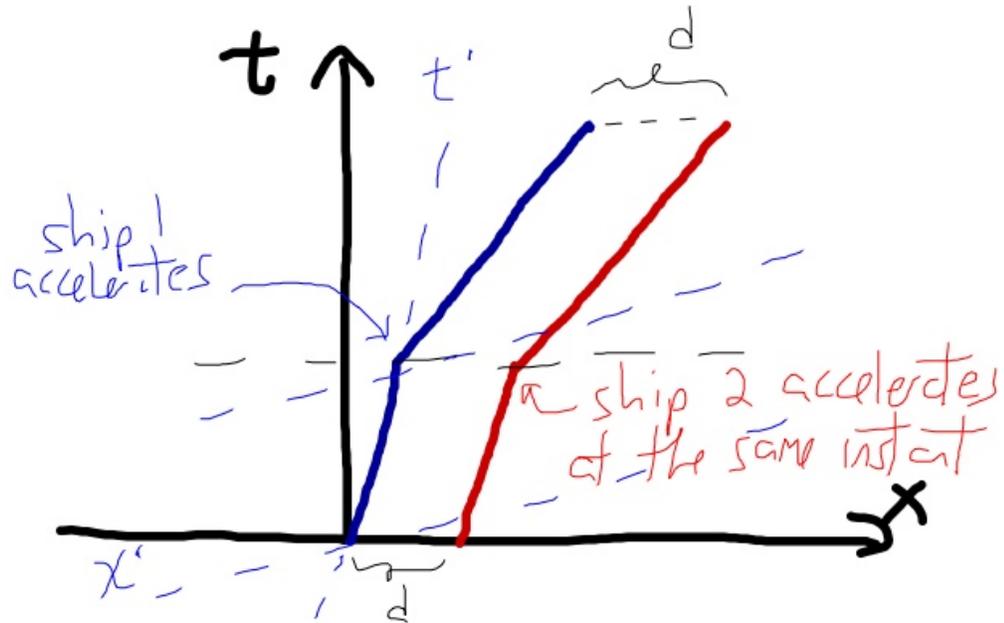
Always the same $v \rightarrow$
always the same d



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4

Who accelerates first?



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Why do the ships get further apart in their reference frame?

We thought the ships were accelerating at the same rate, thus keeping a constant distance.

But things aren't so simple -- since "they hit the gas pedal *at the same time*" is a frame-dependent statement, "they accelerate at the same rate" also turns out to be frame-dependent.

The two ships think they have different accelerations - **basically because their metersticks are getting shorter.**

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Question:

The distance between the two ships can't stay the same in my reference frame *and* in their reference frame.

If the rope were really strong (“unbreakable”), then in which reference frame (if either) would the distance stay the same?

But if the distance between the two ships “stretches,” why doesn't the rope “stretch” too?

Remember Einstein's premise

Define time and space *by* physics rather than *assuming* their universal existence outside of the laws of physics.

Time is what a clock measures; distance is what a ruler measures.

What determines the length of a ruler?

We can no longer just say “this ruler is a meter long,” because a meter means different things to different observers. Or could the ruler just choose to be any length it likes? Something *makes* it the length it is, and this is *physics*. Something holds the ruler together.

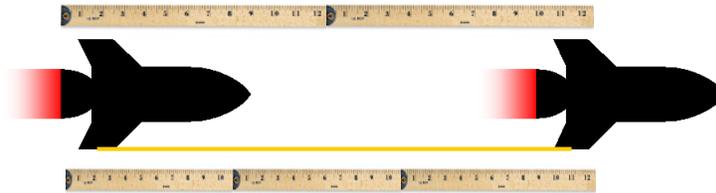
Physics is geometry

BUT

Geometry is physics!

Recall my earlier statement:

Unless the rope gets longer in the ships' frame, it must break (or pull the ships closer together).



NOTE: if the rope were really strong, and *forced* the two ships to get closer, then the two ships would form a kind of ruler: some laws of physics (built into the rope) would determine their distance.

But without such a strong rope, there's no *force* preventing me from moving the two ships independently, and they need not

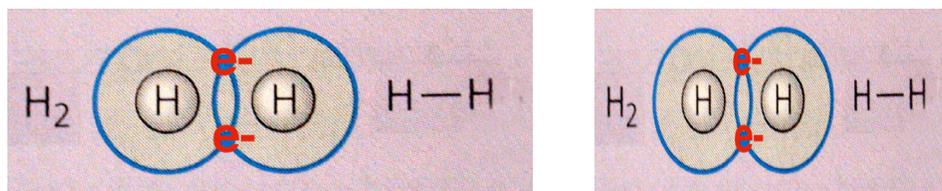
- get closer (in my reference frame)
- stay the same distance apart (in their reference frame)

The contraction is *real*

Remember that this started because the laws of electricity & magnetism didn't "look the same" at all speeds, according to Galileo.

Replacing Galileo's frames with Einstein (& Lorentz *et al's*), we find the laws *do* look the same -- and not just em laws, but *all laws of physics*.

This guarantees that something in those laws must actually make objects shrink.



new, magnetic, force when the atoms are moving, pulls them closer together

Must we even think about reference frames?

Not really -- if you understand the laws of physics from the earth's perspective,

you can figure out that moving objects really *do* "slow down" and contract;

since this includes the moving rulers & clocks, you know the moving observer won't see it this way.

But didn't we *start* with an assumption about ref. frames?

Was it really an assumption?

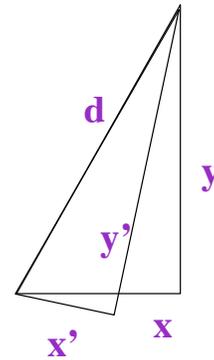
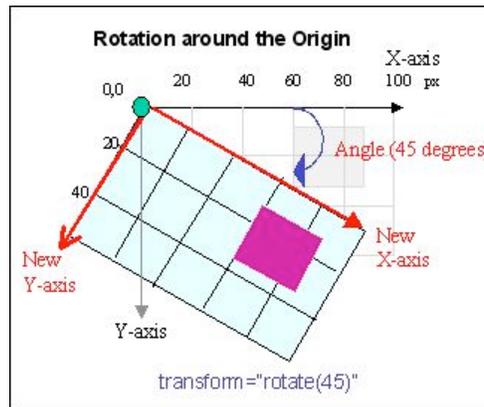
We find that if I rewrite positions and times according to some funny formulas, the laws of physics in terms of x' and t' look exactly the same as they do in terms of x and t .

Galileo just says $t'=t$ and $x'=x+vt$; Lorentz & Einstein are messier. But that's just math; why *shouldn't* there be *some* such way to write it?

What Einstein does is to say the following: if the laws of physics make meter sticks 1 metre long in x when x isn't changing, then the same laws will make meter sticks 1 metre long in x' when x' isn't changing.

These x' and t' variables, as funny as they may look, *must* tell us what distance and time will feel like if we use moving rulers and clocks.

Invariants...



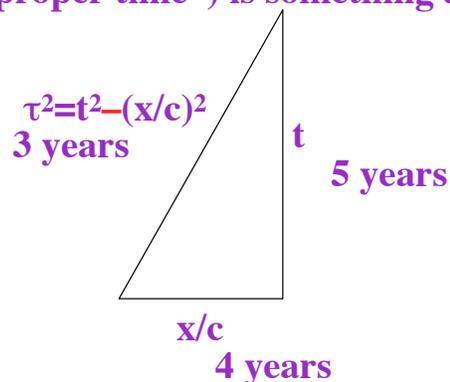
Simple rotations:

You might describe a place with different “coordinates,” and I’ll say $d^2=x^2+y^2$ and you’ll say $d^2=x'^2+y'^2$ but it’s the same d .

Invariant in relativity?

I may think it took 5 years for you to get to α -Centauri, and you may think it only took 3 – but we both agree that you only got 3 years older.

Your own age (“proper time”) is something all observers agree on.



Note: in the end, Einstein seemed to think space and time don’t even exist; the only things which are *real* are these invariants, and we can draw whatever pictures we like, so long as we don’t mess with those.

Could it be that space and time are merely human constructs?

Philosophical addendum

After the long search for an “ether” which would describe a “true rest frame,” a big part of Einstein’s programme was to show that there is *no* “preferred rest frame” -- an egalitarian theory of observers, a universal theory of physical laws.

This is generally how relativity is taught: all about reference frames. This leaves even many physicists *incorrectly* believing that it’s all a matter of optical illusions, and the contraction isn’t real.

Bell’s point in the spaceship example was to show that this is not a consistent viewpoint. The effects *are* real. In fact, one could completely leave out any discussion of reference frames, and do physics in one supposed “preferred frame.” One would find that the laws of electromagnetism directly predict the contraction of matter (since matter is held together by em forces).

Then one would discover (as Galileo did for the laws of mechanics) that these laws *happened* to look the same for other non-accelerating observers... and that all the other laws of physics happened to obey the same principle...

What about mechanics?

Something else clearly does need to be modified.

Newton says that if you apply a constant force, you get a constant acceleration - velocity keeps growing forever.

We’ve now seen velocities can’t grow forever: if you try to add $0.9c$ to another “boost” of $0.9c$, you get $0.99c$, not $1.8c$...

It is harder to accelerate rapidly moving objects.

Can we still use $F=ma$?

If we still want to use $F=ma$ (this is the only definition we have of mass anyway*, so there’s no reason to change it), what must we conclude?

*There are actually two definitions of mass, inertial and gravitational... more on this soon!

For the same force, the acceleration gets smaller;
this means **the mass gets bigger** for faster-moving objects...

Energy is a form of mass.

And logically, mass must also be a form of energy.

$$E=mc^2$$

The “c” is just a constant, a conversion between units of mass and energy. Einstein would rather have said “ $E=m$,” and taught us to stop using different units for energy and mass. (He would also like to say “ $x=t$ ” and get us to stop using different units for space and time.)

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Cons'n of momentum in 2 frames



If two objects push each other, equal and opposite force \rightarrow they will move apart with equal & opposite velocities, so total momentum = 0.

But in a frame moving to the left, the particle on the left now appears to have stopped, while the one on the right is moving faster.

In Galilean relativity, the object on the right would be moving at $2v$ – I would conclude that the momentum of one object at $2v$ is the same as the momentum of two objects at v . But in SR, $0.5c + 0.5c = 0.8c$ – so Einstein concludes that the momentum of one object at $0.8c$ is *twice* the momentum of a object at $0.5c$; this is because it's gotten massive.

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$$E=mc^2$$

How big is this c^2 ? $(300\,000\,000\text{ mps})^2 = 90\,000\,000\,000\,000\,000\text{ m}^2/\text{s}^2$

When 4 grams of Hydrogen in the Sun fuse to make 4 grams of Helium, it turns out Helium is a *little lighter* than 4 Hydrogen atoms, so they only make about 3.97 grams of Helium. Those extra 30 mg of missing matter? They make about 3 *trillion* Joules (about a million kW-hrs).

If you could convert 1 kg of something *entirely* to energy, you could replace every power plant in North America for about a day. Or destroy 1000 Hiroshimas.

This is why Szilard (who came up with the idea of the chain reaction), Teller, and Wigner were so scared of the idea of someone *else* making a nuclear bomb, and convinced Einstein to write to the U.S. president suggesting he do so first...

Albert Einstein
Old Grove Rd.
Nassau Point
Peconic, Long Island

August 2nd, 1939

F.D. Roosevelt,
President of the United States,
White House
Washington, D.C.

Sir:

Some recent work by E. Fermi and L. Szilard, which has been communicated to me in manuscript, leads me to expect that the element uranium may be turned into a new and important source of energy in the immediate future. Certain aspects of the situation which has arisen seem to call for watchfulness and, if necessary, quick action on the part of the Administration. I believe therefore that it is my duty to bring to your attention the following facts and recommendations:

In the course of the last four months it has been made probable -

Einstein, later:

I do not believe that civilization will be wiped out in a war fought with the atomic bomb. Perhaps two-thirds of the people of the earth will be killed.

I know not with what weapons World War III will be fought, but World War IV will be fought with sticks and stones.

J. Robert Oppenheimer later:

- Now I have become death, the destroyer of worlds. (quoting Bhagavad Gita)
- the physicists have known sin; and this is a knowledge which they cannot lose.
- There must be no barriers to freedom of inquiry ... There is no place for dogma in science. The scientist is free, and must be free to ask any question, to doubt any assertion, to seek for any evidence, to correct any errors. Our political life is also predicated on openness. We know that the only way to avoid error is to detect it and that the only way to detect it is to be free to inquire. And we know that as long as men are free to ask what they must, free to say what they think, free to think what they will, freedom can never be lost, and science can never regress.
- But when you come right down to it the reason that we did this job is because it was an organic necessity. If you are a scientist you cannot stop such a thing. If you are a scientist you believe that it is good to find out how the world works; that it is good to find out what the realities are; that it is good to turn over to mankind at large the greatest possible power to control the world and to deal with it according to its lights and its values.

But back to physics...

What is mass?

(1) Mass tells us how fast something will accelerate under a force. **“inertial mass”**

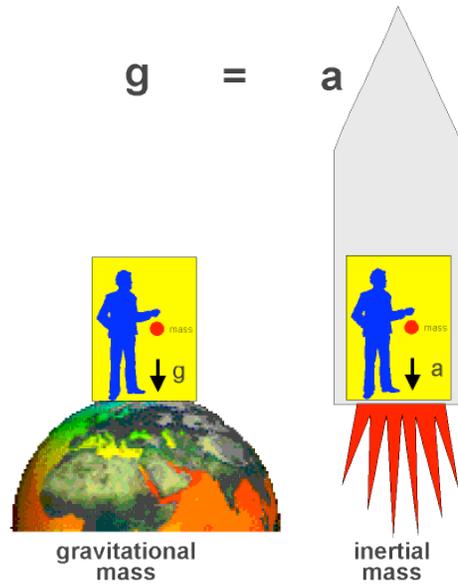
(2) Well, except gravity - everything accelerates the same.

(3) Newton: OK, then mass also tells us how *big* the gravitational force is. **“gravitational mass”**

(4) Einstein: Too much of a coincidence.

Maybe gravity *isn't a force at all*.

How can you tell there's gravity?



The “equivalence principle”: there is no way to tell if you feel gravity or if you are accelerating.

Gravity is the difference between an “inertial” (freely-falling) reference frame and an accelerating frame, and that’s it.