Je ziet 't pas als je 't door hep.

You won't see it until you grasp it.

Als ik zou willen dat je 't begreep, zou ik het beter hebben uitgelegd.

If I would like you to understand it,
I would have explained it better.

Johan Cruijff (1947-2016)

General relativity

predicts frame dragging by a rotating body,
causing orbiting bodies to perform a bit more rotation
around the orbited body than only their orbital velocity.

It follows from e.g. the Kerr solution of the Einstein equation
(see https://en.wikipedia.org/wiki/Kerr_metric
& https://en.wikipedia.org/wiki/Frame-dragging).

But do you really *understand* frame dragging, or is it merely
a flawless mathematical result that you take for granted?

Can ***YOU*** explain it in such a way that a high school student
gets to the bottom of ***why*** & ***how*** frame dragging occurs?

I mean: ***explain*** in a physical way without advanced maths?

In http://henk-reints.nl/astro/HR-Relativity-and-curvature-of-spacetime.pdf, I explain:

When accelerating, you build up a velocity with respect to the uniform motion you would have had without acceleration. Acceleration is caused by a force, so when you are subject to some force, you build up a velocity with respect to the inert motion you would have had without that force.

Einstein's happiest thought of his life was: *In free fall you don't feel your own weight. During a free fall in a gravitational field, you can very well substantiate that you're at rest or in inert motion.*

To be (radially) stationary in a gravitational field, an upward force is required that prevents your free fall. In practice, it will be exerted by the resilience of the (nearly) incompressible matter forming a planet. It *is* what you feel with your bottom when sitting on the floor or on a chair.

The (pseudo) acceleration caused by this force yields an effective (gravitational pseudo) velocity (=: "*gravocity*") w.r.t. your inert motion, which is the free fall. Obviously, this *gravocity* equals the escape velocity. Since the latter does not actually change, the *gravocity* is constant, despite a continuous force being exerted. Whilst sitting on a chair, you effectively have an upward velocity of 11.2 km/s! Like any velocity, the *gravocity* causes kinematic time dilation, including all of its consequences. *That* is the so-called Equivalence Principle[1].

Since your inert motion (free fall) decreases with height, you *effectively* decelerate w.r.t. it when in uniform upward motion and you *effectively* accelerate in uniform downward motion. Uniform upward motion becomes more inert & downward less.

[1] See http://henk-reints.nl/astro/HR-Equivalence-principle.pdf

We define: $\rho \coloneqq r/r_\mathrm{S}$ where $r_\mathrm{S} = 2GM/c^2$ = Schwarzschild radius.

Then: $\beta_\mathrm{grav} = \beta_\mathrm{ff} = \sqrt{1/\rho} \therefore \beta_\mathrm{grav}^2 = 1/\rho$

and: $\boldsymbol{g} = \frac{F_\mathrm{g}}{m} = \frac{GM}{r^2} = \boldsymbol{\frac{c^2 r_\mathrm{S}}{2r^2}} \therefore \boldsymbol{g}\frac{r_\mathrm{S}}{c^2} = \frac{r_\mathrm{S}^2}{2r^2} = \frac{1}{2\rho^2} = \frac{\beta_\mathrm{grav}^4}{2}$

Dimensionless gravitational acceleration: $\tilde{\mathfrak{g}} \coloneqq \frac{g r_\mathrm{S}}{c^2} = \boldsymbol{\frac{\beta_\mathrm{grav}^4}{2}}$

Now we (*relativistically*) add the *true radial velocity* w.r.t. the central mass to the *gravocity* (*both: outward = positive*), yielding an *effective velocity* (*w.r.t. inert motion*) and what I'll coin *gravitational pull* (please interpret that a bit vaguely; it is *not* the same as *force*):

$$\tilde{\mathfrak{g}}_\mathrm{eff} = \boldsymbol{\beta_\mathrm{eff}^4/2}$$

The greater the true velocity (*w.r.t. gravitating mass*), the greater "normal" SR-effects will be. Obviously, it modifies the *effective velocity*, which in turn yields the *gravitational pull*, which would influence ***all*** gravitational effects.

It implies a (small) mass undergoes more *gravitational pull* when moving away from a large mass and less when moving towards it, although a different *force* is only felt if truly accelerating.

As if you're in a lift. Erfahrung!

(Einstein always referred to Erfahrung = *experience* in order to substantiate things).

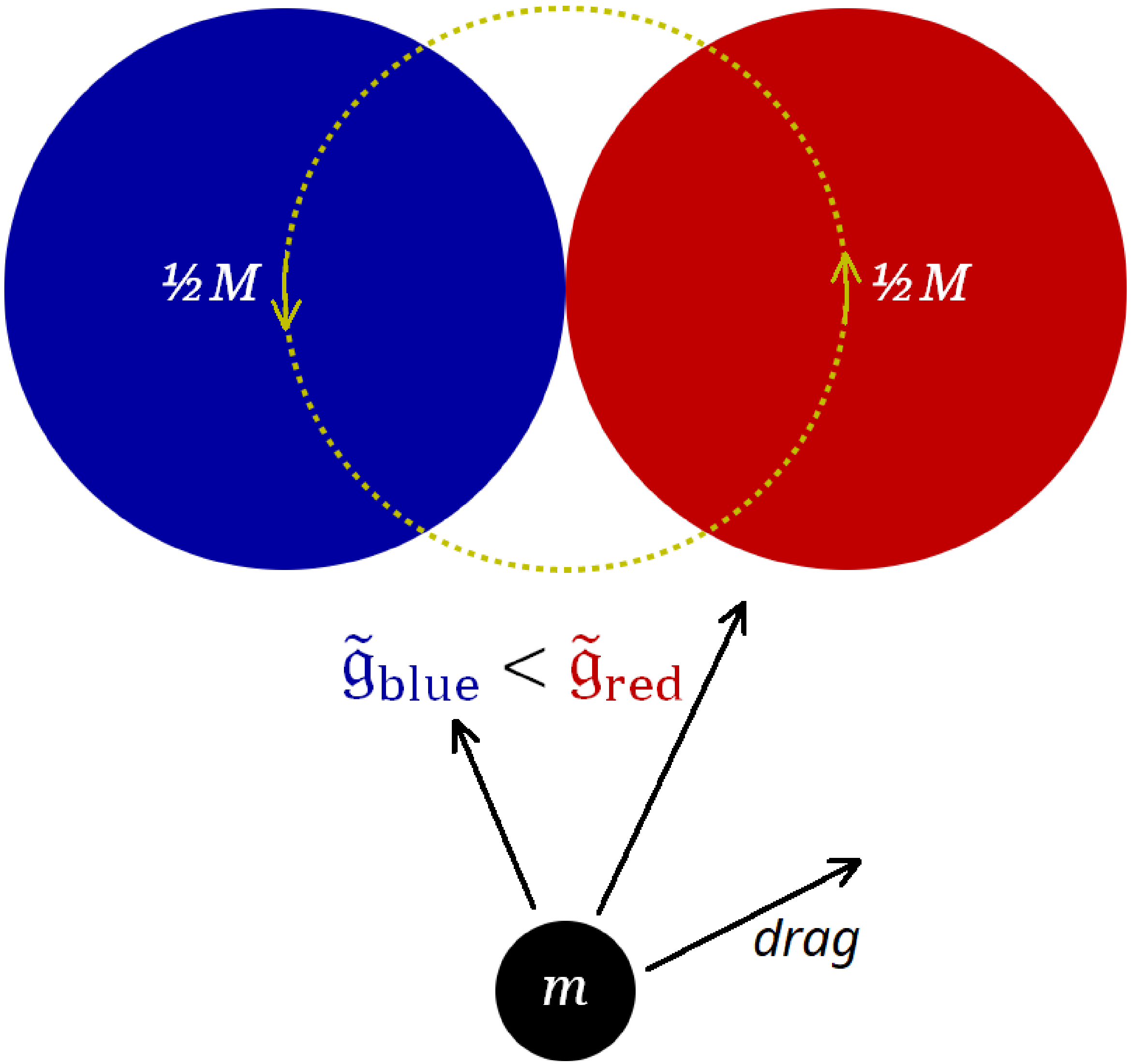
Less pull is required if already approaching and more if trying to escape; *descending is easier than climbing.* Erfahrung!

The pull goes all the way to zero in case of a truly free fall and then ***no*** net force is exerted (until you hit the flooHoHoHaHaHahOuch! 😋🥴).

The common barycentre
of a heavy and a small mass
follows just one trajectory,
while the heavy mass
drags the smaller one along if it doesn't keep up
and pulls it back if it walks ahead.

Now there are *two* heavy masses.
A small mass then forms a
barycentric system with each of them
and it is mandated to follow both.

Suppose those two heavy masses are orbiting their common barycentre and a small mass is orbiting both of them in their orbital plane, with a period exceeding that of the heavy pair. One of them is **moving away** from it, the other is **approaching** it, so it perceives more gravity from the **red** one than from the **blue** one.



Look what happens:

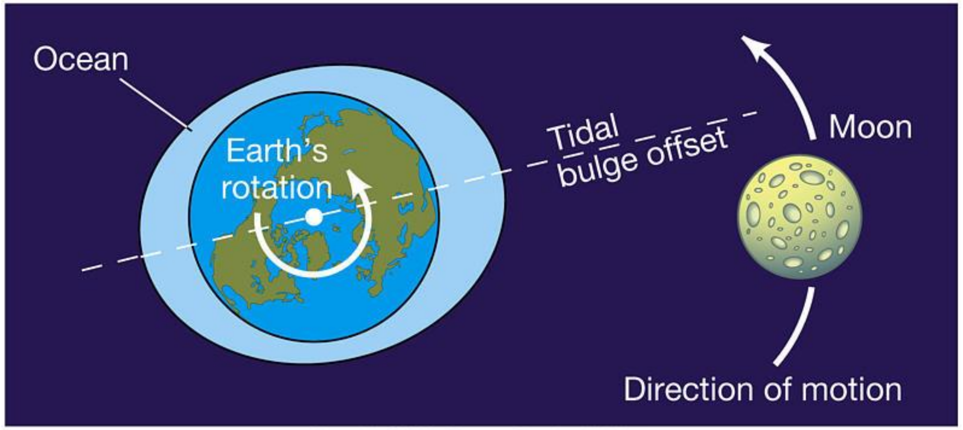
Now suppose those **red** and **blue** masses are the eastern & western hemisphere of a rotating single spherical body around which a planet or satellite is orbiting... ☺👍.

https://images.kinorium.com/movie/shot/54858/h280_238356.jpg

General Relativity is not necessary to (qualitatively) **explain frame dragging.** And wouldn't *orbit dragging* be a better term?

Note: the smaller mass should orbit slower than how the central mass rotates. Otherwise, it would be pulled harder by the **blue** hemisphere than by the **red** one, braking it into an inward spiral.

The very same applies to tidal drag. Within the geostationary orbit, satellites will spiral in, cf. Mars' moon Phobos.



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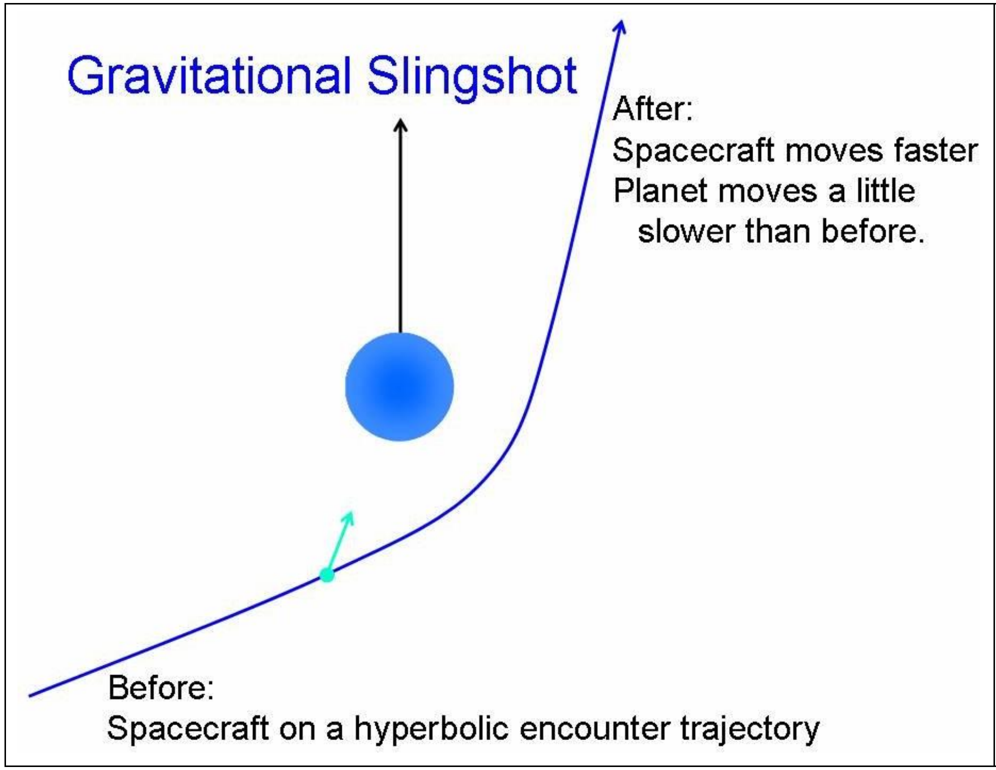
https://www.askamathematician.com/wp-content/uploads/2013/10/FG07_23.jpg

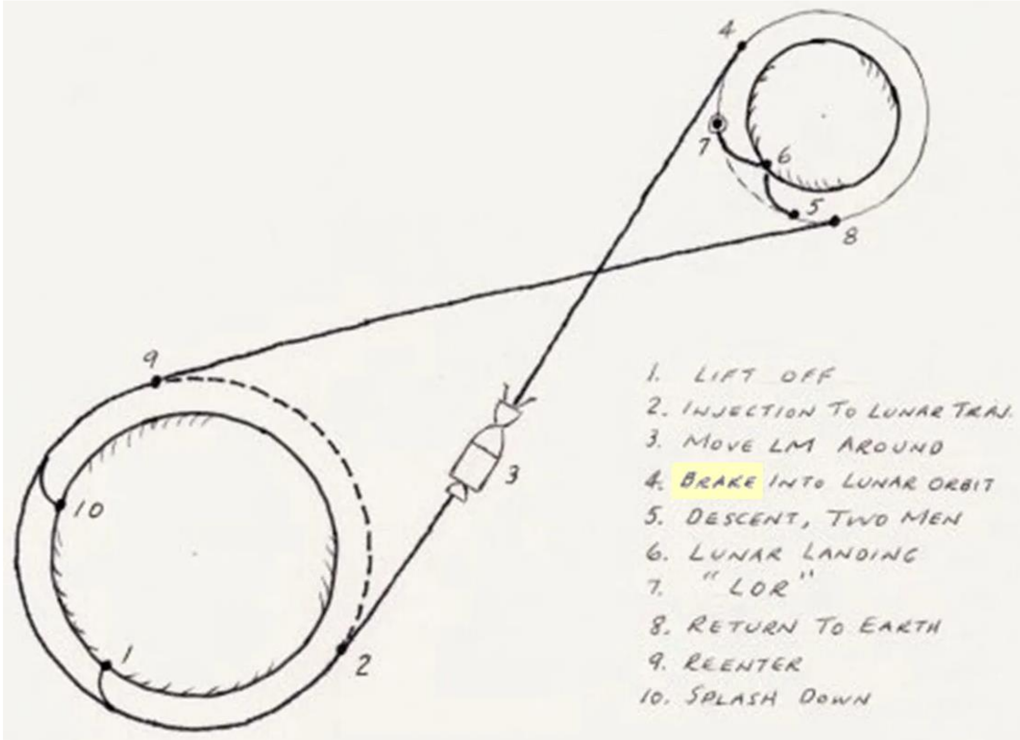
Due to friction, Earth's tidal bulges aren't lined up with the moon. One bulge is closer to the moon than the other, so the moon is pulled forward, thus increasing its orbital velocity, which makes the moon "go off the rails" and it leaves Earth at ~38 mm/yr.

Isn't this ~~*frame*~~ *orbit dragging* by the tidal bulges?

Wouldn't "relativistic" dragging cause distantiation as well?

And isn't a **gravitational slingshot** a sort of frame dragging?

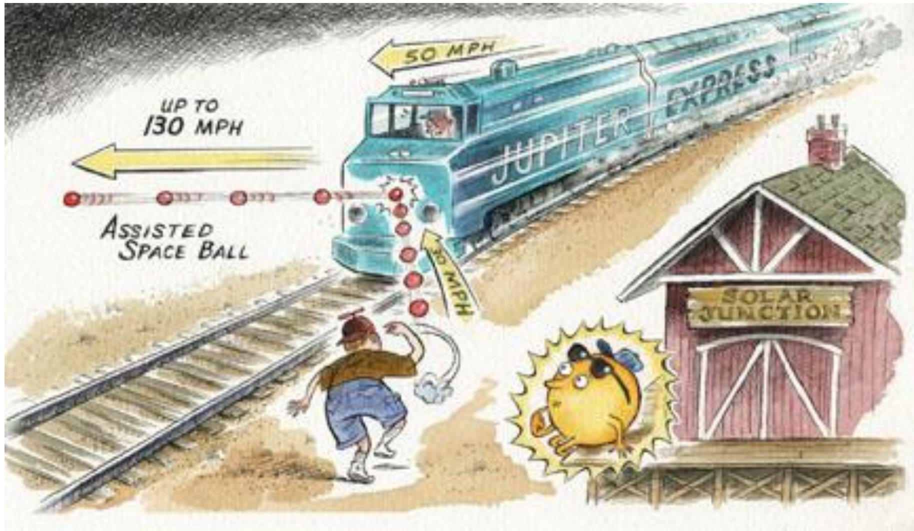




Pass behind a planet: speed up,
i.e. kinetic energy is transferred
from planet to spacecraft.

Pass in front of moon: *BRAKE*,
i.e. kinetic energy is transferred
from spacecraft to moon.

https://space.stackexchange.com/questions/10195/why-did-voyager-2-receive-a-gravitational-slowdown-as-opposed-to-a-slingshot-a
https://www.bbc.com/future/article/20160414-the-decision-that-saved-apollo-13



Ball thrown at 30 mph w.r.t. thrower hits front of oncoming train driving at 50 mph w.r.t. thrower. Ball speed w.r.t. train $= 50 + 30 = 80$ mph. Bounce back w.r.t. train $= 80$ mph. Must yet add train's velocity w.r.t. thrower, i.e. returned ball speed w.r.t. thrower $= 50 + 80 = 130$ mph towards him.

https://space.stackexchange.com/questions/9504/how-can-i-intuitively-understand-gravity-assists/9505#9505

When trying to hit back of train, ball must be thrown faster than train's velocity, say it's thrown at 60 mph. Ball speed w.r.t. train then merely 10 mph. Bounce back also at 10, yet to be subtracted from speed of train (which is going away from thrower), yielding 40 mph w.r.t. thrower (ball still going away from him). *It slowed down, but not nearly as much as the speed-up when hitting the front.*

Bouncing is similar to repulsive gravity, so in space you gain speed when approaching from behind and you loose speed when passing in front of a planet.

General Relativity

is ***not*** necs. to (qualitavely) explain frame dragging,

NOR to derive and ***UNDERSTAND***
Mercury's ~~perihelion~~ ***orbit*** precession:
http://henk-reints.nl/astro/HR-Mercury-perihelion-precession-by-SR-only.pdf

NOR to explain and ***UNDERSTAND*** the factor of 2
in the deflection of light skimming the sun:
http://henk-reints.nl/astro/HR-Deflection-of-light-passing-a-mass.pdf

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