



the different faces of time in physics

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Toni Verdú Carbó

Augustine
354-430 C.E.

*Quid est ergo tempus? Si nemo
ex me quærat, scio; si quærenti
explicare uelim, nescio.*



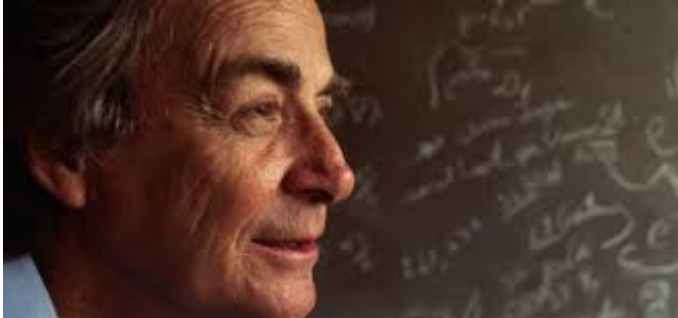
“What, then, is time? If no one asks me, I know; if
I wish to explain to whoever asks, I know not.”

slogans



- Time is what stops everything happening at once.
John A. Wheeler/Albert Einstein
- Time is Nature's way of getting round the law of non-contradiction.
- Instants are not in time. Time is in instants.
Julian Barbour
- Time is money.
Benjamin Franklin

Time is "a snake eating its tail".
Kurt Vonnegut Jr.



Richard Feynman
1918-1988

“ Maybe it is just as well if we face the fact that time is one of the things we probably cannot define ... What really matters anyways is not how we define time, **but** how we measure it. ”



in physics, time is not just one thing

it is not a “thing” at all:

it cannot be “measured”

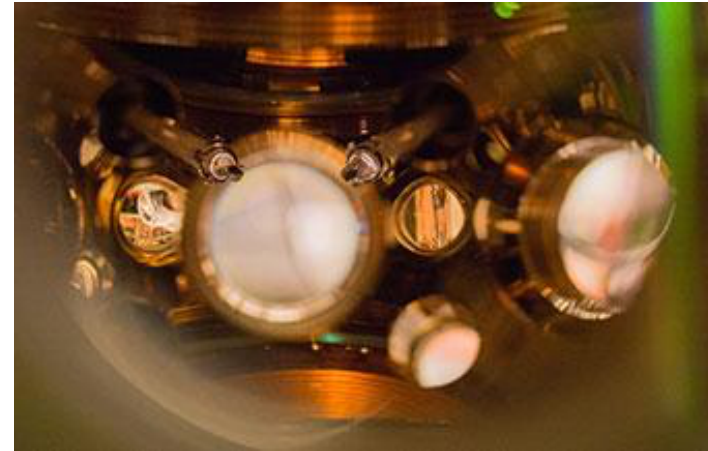


vs.





VS



Credit: Marti/JILA

digital quartz crystal stop watch
accurate to $\frac{1}{4}$ second per day.

strontium lattice atomic clock 2015
accurate to within 1 second in 15 billion years
— the age of the universe



before and after: the arrow of time I

two faces of simultaneity II

duration (connection with clocks) III

duration and Einstein: motion dilation and “gravitational” dilation IV

the arrow

of time



- “Instants are not in time. Time is in instants” (Barbour)

plants can be stop-watches with memory



Thale cress or mouse-ear cress
Arabidopsis thaliana



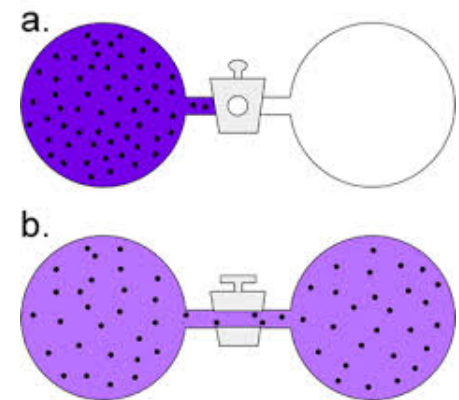
vernalization: necessary for
flowering

plant measures the duration of
cold

and remembers the winter
effect for months



Boltzmann's H-theorem 1872



Q: Is the entropic arrow of time “paradoxical”?

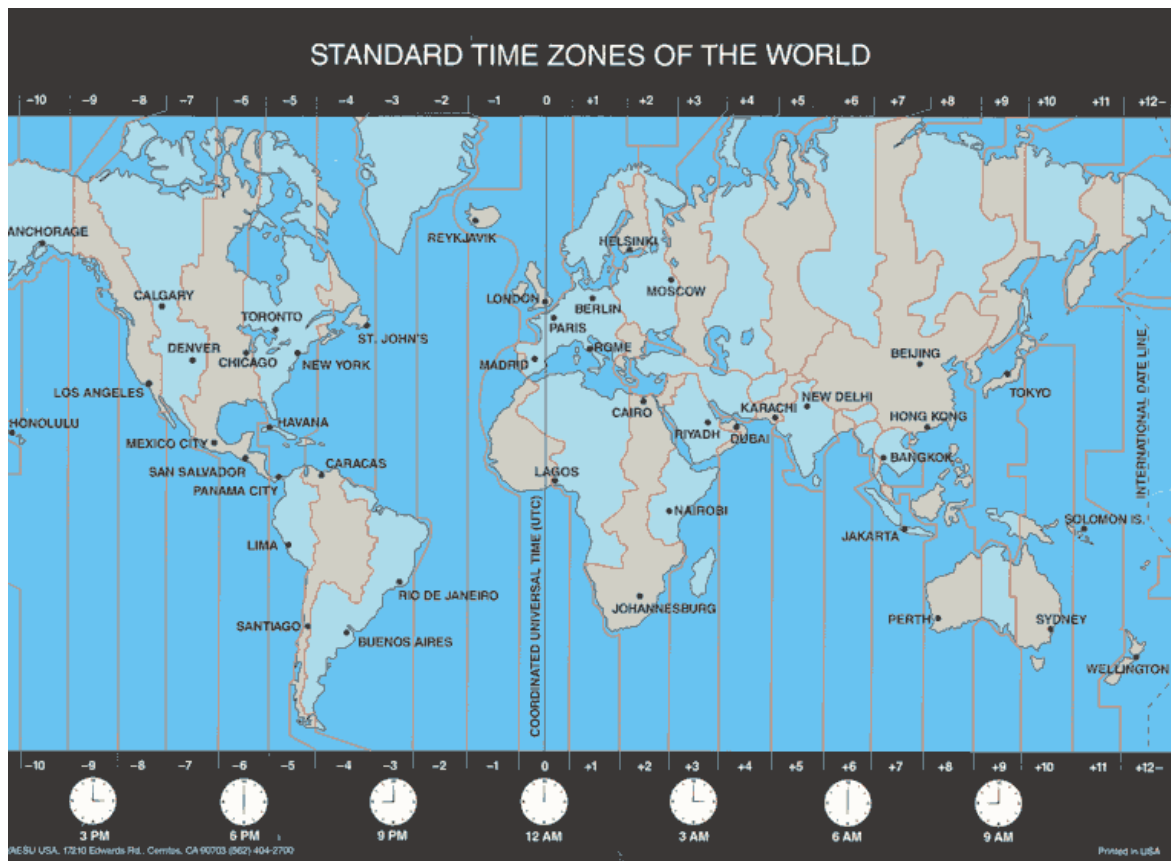
A: No. But there are puzzling aspects to it.

why do we see so many isolated systems in
the universe displaying the same arrow?



simultaneity I: its conventionality





Time zones
remind us:

- that we spread time across space on grounds of convenience
- that as a result we may end up traveling backwards in time
- to ask what the “true” simultaneity is behind the convention



synchronized
separated clocks

or are they?



Time is (standardly) spread through space so that the one-way speed of light is the same in all directions (i.e. “isotropic”).



This is the Poincaré-Einstein convention



It simplifies our equations in physics!

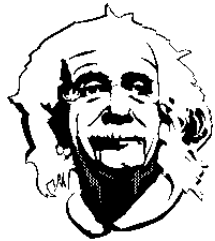


simultaneity II: its relativity





Henri Poincaré realised before Einstein if all observers use this convention, the result is the **relativity of simultaneity**.



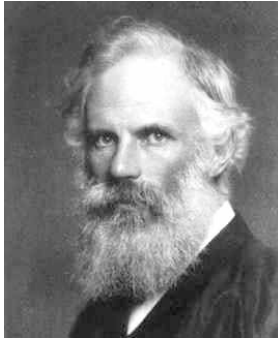
“For us devout physicists, the division between past, present, and future is only an illusion, if a stubborn one. ”
Einstein 1955

does time flow?



temporal duration





the problem of the standard of time



G. F. FitzGerald
(1890s) :

“ ... there is every reason for assuming that the Earth rotates on its axis more uniformly than any clock we can construct”.

But the rotation rate is changing: 5 hours over last 3000 years
testimony of ancient eclipses
frictional resistance of the tides (slowing)

So “. . . how on earth can we discover a change in our standard itself?”

How do we find a “more ultimate standard of time”?



the dynamic Earth

main slowing mechanism: **tidal braking** (two milliseconds over the past two centuries)
first postulated by Immanuel Kant in 1754. too big over last millennia!

other influences affecting the **shape** of the Earth:

redistribution of mass on surface of the Earth; glacial cycles; recently viscous rebound

core-mantle coupling: shifting exchanges of angular momentum between the Earth's liquid core and the mantle

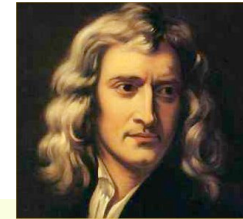
rise of sap in trees!

what is duration?



duration is defined by ideal clocks (Einstein)

What is an ideal clock?



ideal clocks are defined by duration. (Newton, FitzGerald, Poincaré, Barbour, ..)

What is duration?

The choice of a certain (“temporal”) parameter that makes the basic laws of physics take their simplest form.

Time is the “great simplifier”.

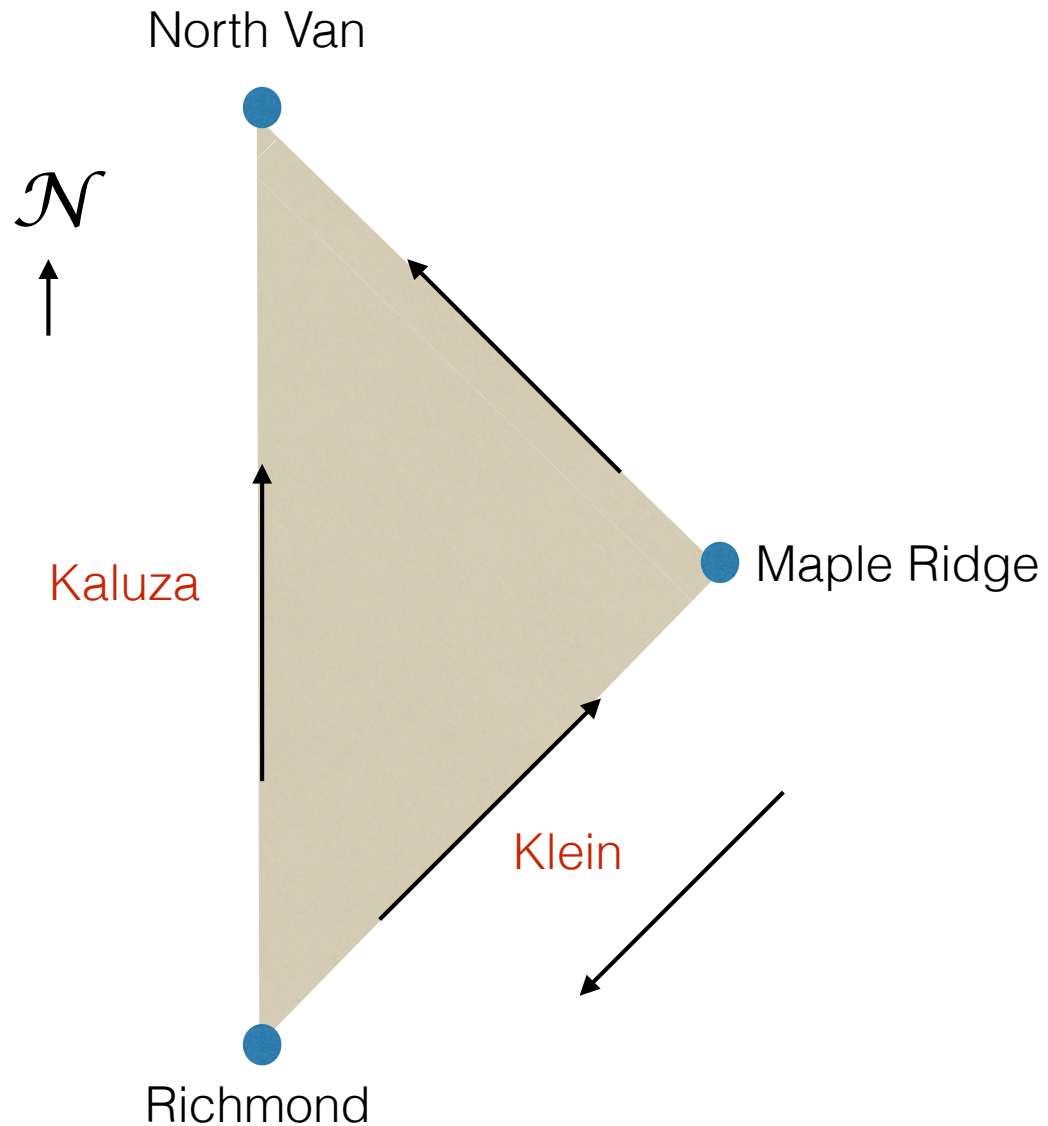
vs.



duration and the effect of motion



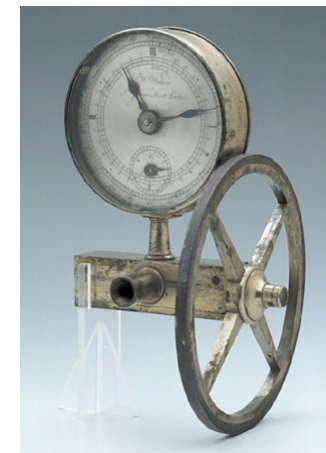
A parable about space: 18th century waywisers



Thomas Wright and William Wyeth, 1740s

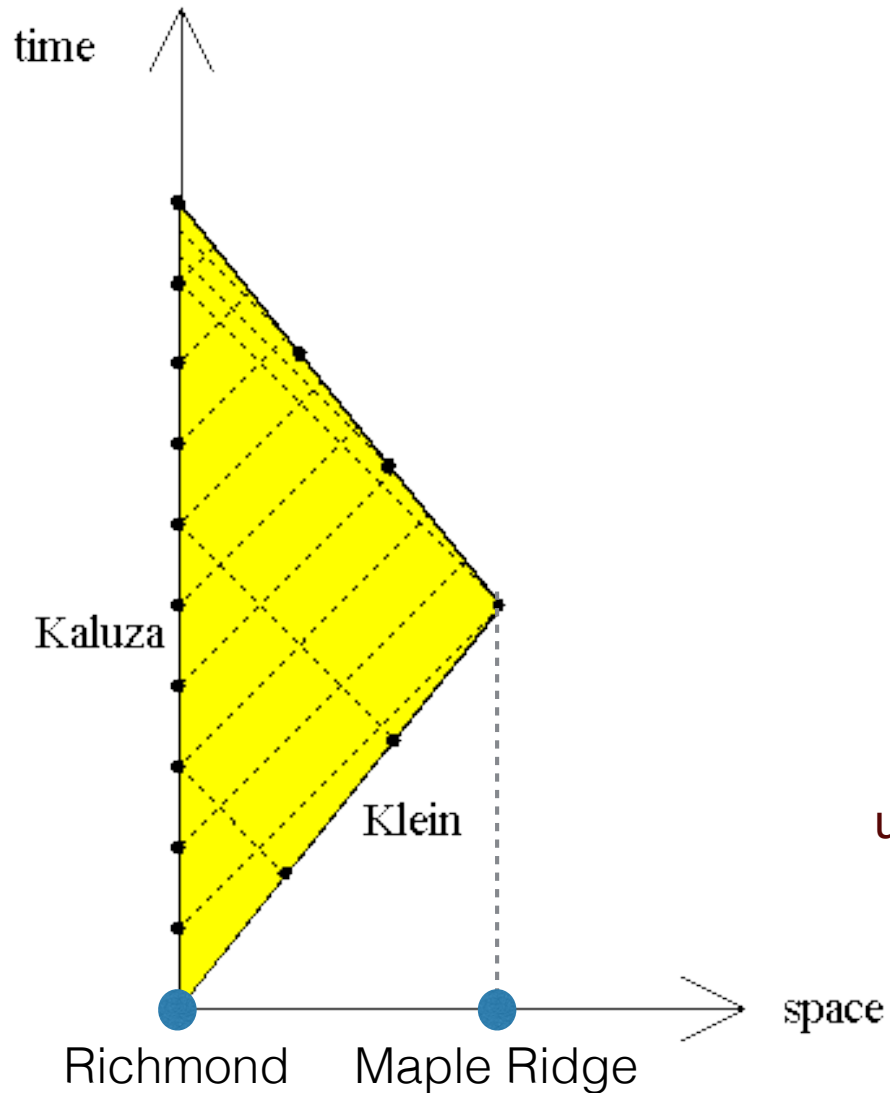


Benjamin Franklin odometer 1760s



William Watkins late 18th century

clock retardation: a result of “time dilation”



a clock is a **waywiser** of
spacetime

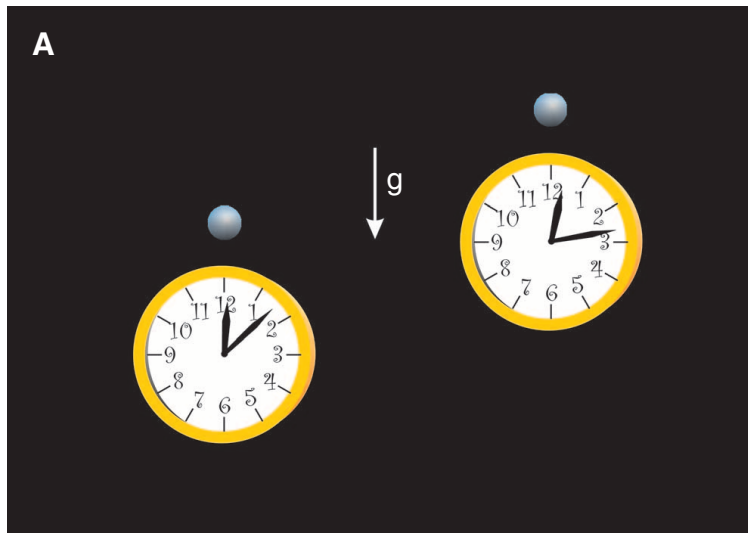
universality: time dilation does not
depend on construction of clock

In 2010, time dilation due to speeds of a few meters per second was detected using atomic clocks





“gravitational” time dilation



if a clock is elevated it goes faster by about 1 part in 10^{16} for each meter its altitude is increased.

GPS has to take into account both motion and gravitational dilation

“... the frequency shift ... is a manifestation of the fact that *time flows at a rate that depends on position within a gravitational field.*”

Eric Poisson and Clifford M Will, *Gravity*, 2014

“... the effect of gravity is not to perturb the operation of a clock but to alter time itself.”

Daniel Kleppner, “Time too good to be true”, *Physics Today*, 2006



How to compare frequencies of accurate clocks at different places on Earth?

Solid Earth tides induce localised fluctuations approaching 20 cm

Oceanic tides, effects of atmospheric pressure on ocean levels

Redistribution of water due to climatic changes

Longer-term effects such as glacial melting and the uplift of tectonic plates.

“ Earth’s gravity is inextricably entangled with time but the Earth shimmies and shakes unpredictably. ”

Daniel Kleppner, “Time too good to be true”, *Physics Today*, 2006

Finally: what is the difference between space and time?

I have run out of the latter!

Thank you.

“Is time an illusion?”

Craig Callender, *Scientific American*, 2010 June; 302(6):58-65

The Labyrinth of Time. Introducing the Universe

Michael Lockwood, OUP 2005

**The End of Time. The next revolution in our understanding of
the universe**

Julian Barbour, Phoenix 2013

From Eternity to Here: The quest for the ultimate theory of time

Sean Carroll, Oneworld 2010

Your Brain is a Time Machine

Dean Buonomano, W W Norton and Co. 2017