Title: Clocks and time in quantum theory

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Abstract: I will examine a number of time-related issues arising in quantum theory, and in particular attempt to address the following basic questions from a quantum perspective: 1. What is a clock? 2. Why do uniformly moving clocks dilate? 3. What is the behaviour of accelerating clocks?

Time and Clocks
and their curious relationship
in quantum theory

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- What is a clock? (Is time "measured"?)
- Time dilation and the "clock hypothesis"

} Periodicity and counting

- Simultaneity: conventionality and relativity thereof

} Phase

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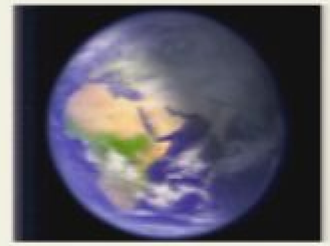
Duration (i)

"We cannot catch a fleeting minute and put it alongside a later minute." Arthur Milne

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:
testimony of ancient eclipses
frictional resistance of the tides

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

How do we find a "more ultimate standard of time"?

What is duration?

Duration is defined by ideal clocks. (Einstein)

What is an ideal clock?

"By a clock we understand anything characterized by a phenomenon passing periodically through identical phases so that we must assume, by virtue of the principle of sufficient reason, that all that happens in a given period is identical with all that happens in an arbitrary period."
Einstein 1910

vs.

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

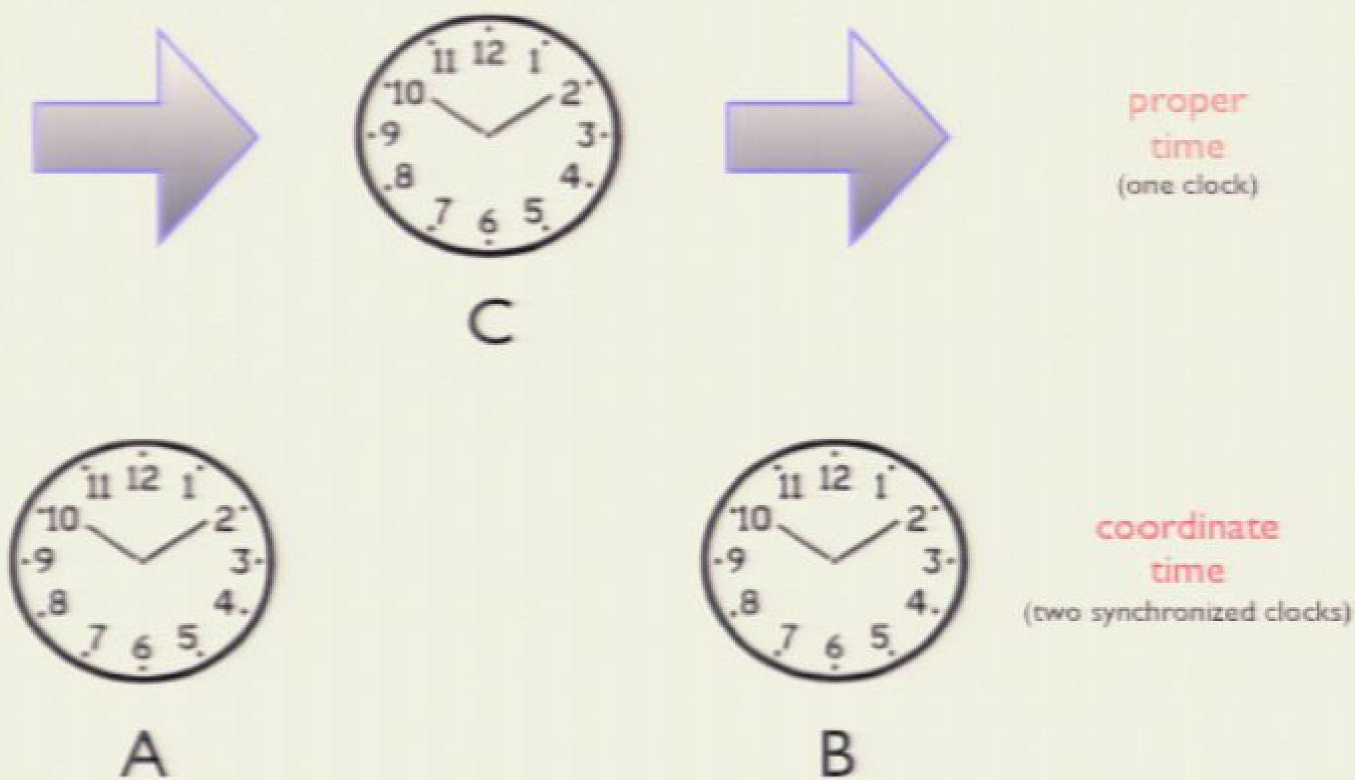
What is duration?

The choice of a temporal parameter that makes the basic laws of physics take their simplest form.

There is no ideal clock (apart from the universe as a whole).

Duration (ii)

Time dilation: difference between proper time and coordinate time



Premonitions of time dilation

Joseph Larmor (1857–1942)

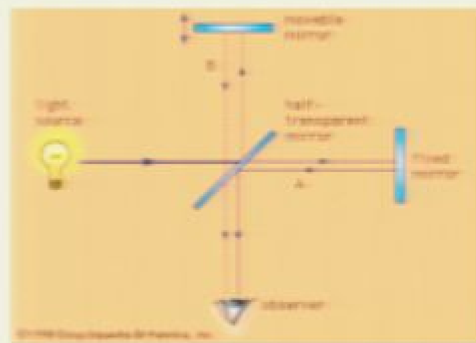
In 1897, predicted time dilation for a moving system of orbiting charged particles (inspiration for Bell 1976?)

Hendrik Antoon Lorentz (1853–1928)

In 1899, independently predicted time dilation for a moving source of monochromatic light.

Janssen (1995)

Ives (1937), Kittel (1974), Bell (1976), vs Rindler (1970)



1888 Liénard version: implies FitzGerald-Lorentz deformation, and (k-dependent) time dilation for light source

How to explain time dilation?

- It is a consequence of Einstein's 1905 principles.
- It takes Minkowski's 1908 geometrization of the theory.
- Appeal must be made to the quantum theory of matter.

Bell's (1976) "Lorentzian pedagogy"

John S Bell
1928-1990

"How to teach special relativity"
Progress in Scientific Culture (1976)

generalized Heaviside's (1889),
inspired by Larmor (~1900)

"The longer road [of FitzGerald, Lorentz, etc.] sometimes gives more familiarity with the country."

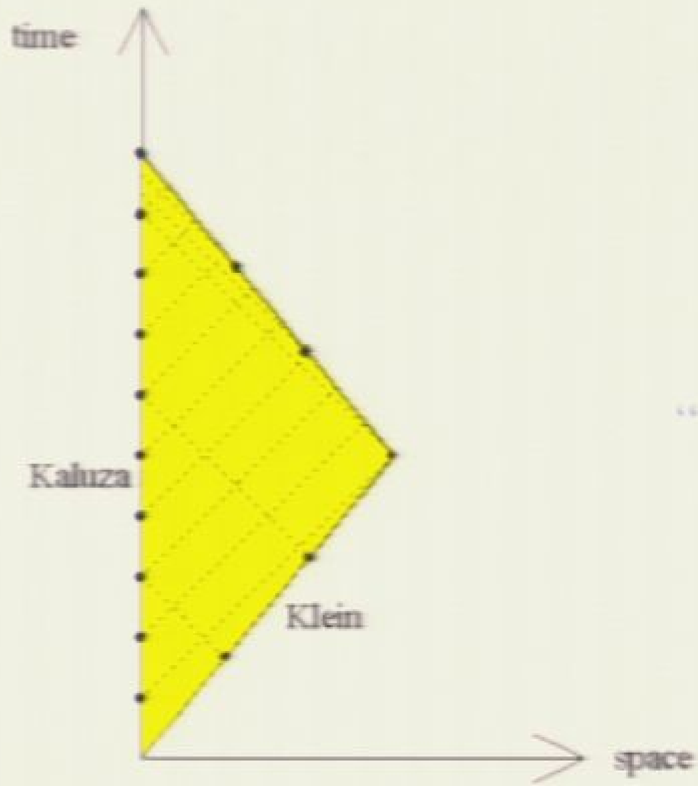
warned against "premature philosophizing about space and time"

"... we need not accept Lorentz's philosophy to accept a Lorentzian pedagogy. Its special merit is to drive home the lesson that the laws of physics in any *one* reference frame account for all physical phenomena, including the observations of moving observers."

Duration (iii)

Clock retardation

Einstein's 1905 discovery



clock as "waywiser"

Arthur Eddington on an accelerating clock:

"We may force it into its track by continually hitting it, but that may not be good for its time-keeping qualities."

C.W. Sherwin (1960) on the 1960 Pound-Rebka "clock paradox" experiment

Then, noting that the electric forces which cause the acceleration act only on the protons, we find that, under accelerations of about $10^{16}g$, the neutron and proton components of the nucleus should suffer a maximum relative displacement of about 1 part in 10^{13} of the nuclear diameter. Even using the great sensitivity of the Mössbauer resonance, such a small distortion is not likely to produce an observable effect.

shift arising from lattice vibrations). We conclude from this rough calculation that the mechanical distortion of the nuclear structure under the accelerations due to the lattice vibrations is very small, but under favorable circumstances an intrinsic acceleration-dependent effect in the resonance frequency might be observable. A detailed analysis based on specific nuclear models is needed for a further evaluation of this possibility. In any case, the experiments to date appear to be adequately explained without recourse to any acceleration-dependent effects.

Phys. Rev. **120** (1960). 120

Anton M Eisele (1987) on the 1977 g-2 CERN experiment

"The g-2 experiment at CERN ... with orbiting muons having $\gamma \sim 30$ had as a by-product that the time-dilatation of Special Relativity was tested and confirmed with an accuracy of 10^{-3}. But the deviation computed here from the behaviour of an ideal clock would be ... less than 10^{-25}, although the muons are experiencing in their orbit a centripetal acceleration of $10^{18}g$!!

Finally, a more speculative extension of our considerations to the very extreme conditions of astrophysics: Near radio-pulsars (quickly rotating neutron stars) magnetic fields up to 2.10^{13} Gauss ... are estimated to exist. Moreover it is believed that there is an e^+e^--plasma with γ-factors up to 10^6. With a possible transition into , a γ-factor of almost 10^4 would result for the muons. In this case ... the correction ... would now give almost 1 per cent! But the most interesting part of this calculation surely consists not in any possible application like this but rather in the possibility in principle to verify the clock hypothesis in this special case with the help of an accepted physical theory."

Helvetica Physica Acta 60 (1987) 1024

Dynamical underpinning of kinematics

H. Weyl 1918, W. Pauli 1921, A.S. Eddington 1928, W.F.G. Swann 1941, L. Jánossy 1971, J.S. Bell 1976, 1992, D. Dieks 1984, 1987, H. Brown and O. Pooley 1999, H. Brown 2005

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Bell 1992 "If you are, for example, quite convinced of the second law of thermodynamics, of the increase of entropy, there are many things that you can get directly from the second law which are very difficult to get directly from a detailed study of the kinetic theory of gases, but you have no excuse for not looking at the kinetic theory of gases to see how the increase of entropy actually comes about. In the same way, although Einstein's theory of special relativity would lead you to expect the FitzGerald contraction, you are not excused from seeing how the detailed dynamics of the system also leads to the FitzGerald contraction."