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Title : **Proper-time measurement in accelerated relativistic systems**

Abstract :

The proposed lecture emerged from a work which addresses the question of *Whether it is possible to assign the concept of common proper-time to complex, spatially extended, relativistic systems as a whole*; in particular, with the wish to use this common proper-time for the *age* of the system.

The process of time measurement uses ideal clocks – inertial point-like clocks – and requires simultaneity between events in the clock system and the measured system. Therefore, in a basic time measurement the clock must be at rest relative to the system in which the measured process occurs.

For a point-like body, the proper-time measurement is identical with the reading of a clock momentarily at rest with the body : An un-accelerated point particle may always be found at rest relative to some inertial frame, so the proper-time measurement for it is identical to the clock reading in that frame. Otherwise, if accelerated, at each and every point along the body's journey in space-time a different ideal clock must be used, relative to which the body is momentarily at rest. Then the proper-time lapse of the particle moving on the world-line $\left(t, \vec{r}\left(t\right)\right)$ relative to some inertial reference frame is the integral $\Delta\tau = \int\sqrt{dt^2 - d\vec{r}^{\,2}} = \int\sqrt{1-\vec{v}^{\,2}}dt$ along the world-line. Since this is the only time measurement available for that particle, it must necessarily serve as the measure for its age.

Real physical systems are not point-like but composite, spatially extended. Even if their constituents may be regarded point-like, these move on different world-lines, each with its own proper-time lapse.

Comparing the proper-time lapses at two different points of the system, say A and B, between any two states of motion, requires using some kind of simultaneity at any of the two states. Since simultaneity is frame dependent and not preserved by Lorentz transformations, much care has to be taken at this point. If the system is inertial there is just one (inertial) rest frame that accompanies the system through its space-time journey, and the correct measurement of proper-time is relative to this rest frame. But if the system accelerates then we must identify a momentary inertial rest frame common to A and B in the initial state, and similarly for the final state, so as to mimic the proper-time measurement for an inertial system.

Therefore, if we want to be able to compare the proper-time lapses at A and B at any stage of the system's journey, then it is required that a momentary inertial rest frame common to A and B must be found at each stage. If A and B are arbitrary points within the system then it implies that the whole system must be moving rigidly. Rectilinear rigid motion is possible for arbitrary (also time-dependent) accelerations (taking into account necessary differential accelerations between different

points), thus making it possible to use rigidly accelerated extended systems to model comparative proper-time measurement.

Since proper-times are Lorentz invariant quantities they should be treated in a Lorentz covariant manner. Linear relativistic rigid motion with general (not-necessarily constant) accelerations is discussed Lorentz-covariantly, allowing to relate accelerations, velocities and proper-times of arbitrarily different points along the moving body. Differential ageing is computed, found to be proportional to the proper spatial distance between the two points and to the rapidity difference between initial to final states.

Once instantaneous simultaneity is determined, the clocks at A and B must be synchronized in some way. This is done using light signals transmitted between the clocks, and the effect of the acceleration on the synchronization is discussed.

Proper comparison of the proper-time lapses at two points of an accelerating system is thus uniquely determined, Lorentz-covariantly, for rectilinear relativistic rigid motion, which may then serve to model comparative proper-time measurement in accelerated relativistic systems.

In particular, this model may be used to consider ideal vs. physical clocks:

The idea of a point-like clock is fundamental for the concept of space-time continuum. It is necessary in order to define a time-like axis. An inertial reference frame in Minkowski space-time consists of point-like clocks moving on parallel time-like geodesics. But point-like clocks are idealizations. Real clocks are composite systems, consisting of many points. If the clock is inertial then all its constituents measure the time equally, which is also the rate that time is measured by the clock. But if the clock accelerates then different constituents of it, moving on different world-lines, may have different proper-time rates. Thus the question arises, *How does this fit with the clock being itself a timekeeping device?* Or, in other words, *What is the relation between the intrinsic time-unit of the clock and external proper-time measurement ?* A discussion of these issues will also be included, as time allows.

Finally, it is important to emphasize that incorrect application of simultaneity to comparative time measurement in accelerated systems (partly due to lack of using Lorentz covariance) leads to wrong conclusions and appearance of so-called `paradoxes'. This will be illustrated with two examples, Bell's spaceships `paradox' and Boughn's `identically accelerated twins'.

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