Time Coordinates versus Clock Readings: Einstein's Struggle with Background Independence and General Covariance

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In his *Autobiographical Notes,* Einstein remarks that when he was working on his general theory of relativity one of the main obstacles for progress was the difficulty that he felt in abandoning the idea that coordinates should possess an immediate physical meaning in terms of distances and clock readings. At first sight, this strikes one as strange: that coordinates are conventional and can be chosen arbitrarily as long as they uniquely identify events seems an obvious fact that was already familiar in pre-relativistic physics. In this contribution we shall further explore the nature of Einstein's difficulties, going from Einstein's 1905 paper on SRT, through his 1907 and 1911 papers on the consequences of the principle of equivalence, to the final GRT of 1915 and later developments.

Obviously, an essential ingredient of the 1905 SRT paper was Einstein's analysis of distant simultaneity. Sometimes Einstein's argument here is represented as an attempt to demonstrate the *conventionality* of simultaneity---but we shall try to make it clear that it makes more sense to say, also in the light of Einstein's work in the years following 1905, that in his SRT paper Einstein wanted to analyze the exact *physical content* of the notion of simultaneity. Conventionality was not the issue at stake, but rather the physical meaning of simultaneity as a real temporal relation.

This is confirmed by Einstein's 1907 and 1911 papers, in which he derives the gravitational redshift from considerations based on the equivalence principle. In particular in his 1911 article, Einstein focuses on the comparison of similarly constructed clocks that find themselves at different positions in a gravitational field. From the point of view of local observers, near to the clocks, these clocks behave identically and tick at the same rate. However, Einstein asks the question whether some of these clocks nevertheless run objectively slower than others, and introduces a criterion to determine this. This criterion involves the introduction of what we now would call a global coordinate time, but which Einstein discusses in terms of clocks that are constructed in such a way that they are able to indicate "true time". Clearly, Einstein here thinks of coordinate time not as a conventionally introduced marker, but rather as a physically meaningful quantity that should be measurable by a clock.

The same line of thought occurs even in the beginning of the 1915 GRT paper, in which Einstein discusses temporal relations on a rotating disk. Here he makes a point of concluding that clocks at the periphery of the disk *really* run slower than a clock at the center, again via the introduction of a global time that is physically meaningful. The notion that global time coordinates should represent clock indications thus had a strong hold on Einstein, even when he formulated his General Theory.

It is clear why Einstein needed global time: we need a global description of situations in order to calculate things like the deflection of light coming from far-away stars, passing by the Sun, and finally arriving at Earth (the best-known subject of his 1911 paper). In special relativity the only way to realize such global descriptions is via the pre-given Minkowski metrical structure, which can simply be related to measurements by rods and clocks. However, in general relativity there is no pre-determined metrical structure---in general we can only assign coordinates in an arbitrary way and leave it to the solution of the Einstein equations to determine how these coordinates relate to physical space and time intervals. The transition from global time as something directly measured by clocks to conventionally chosen temporal coordinates whose physical meaning is still to be determined is thus closely connected to the transition from SRT to the generally covariant and background-independent theory of general relativity.

It is understandable that Einstein had trouble fully adapting himself to the viewpoint of background-independence and only gradually became completely comfortable with the idea that space-time

coordinates are conventional. The discussion of this historical episode is interesting not only for the perspective it opens on Einstein's early thinking, but also for the insight it offers into some relativistic effects like gravitational red-shift and light deflection.

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