Is Time Dilation ‘Real’?

Einstein and the Transverse Doppler Effect

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Introduction

Over the last two decades, philosophical debate on whether special relativistic effects (length contraction and time dilation) call for:

- **dynamical explanation**: length contraction and time dilation reflect changes in the equilibrium configurations of moving material systems (Brown 2005; Brown and Pooley 2006; Brown and Read 2022)
  - real physical changes
- **kinematical explanation**: these effects follow from the Lorentz transformations once rods and clocks are used to assign coordinates (Norton 2008; Janssen 2009)
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  - ‘apparent’: it is a coordinate effect that vanishes for a suitably chosen comoving observer
  - ‘real’: it is empirically testable by any non-comoving observer, provided that the new kinematics holds
    - stresses in the rotating disk
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- a **dynamical explanation** is needed for why atomic clocks of the same kind have the same intrinsic frequency when compared at relative rest
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Part II

Time Dilation and Transverse Doppler Effect in the 1905 Relativity Paper

Time Dilation in 1905

In §4 of the 1905 paper, Einstein draws testable consequences from the new kinematics:

- for a clock permanently at rest in K', one has $x' = 0$
- from the Lorentz transformations:

$$x' = \gamma(x - vt), \qquad t' = \gamma\left(t - \frac{v}{c^2}x\right)$$

- hence $x = vt$ and

$$t' = t\sqrt{1 - \frac{v^2}{c^2}}, \qquad \Delta t = \gamma \Delta t'$$



Clock retardation per unit time is a second-order effect: $\Delta t/t \approx \frac{1}{2}(v/c)^2$.

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In §7 of the 1905 paper, Einstein applies the new kinematics to optical plane waves.

- the invariance of phase yields the relativistic Doppler formula:

$$\nu = \nu' \frac{1 + \frac{v}{c}\cos\varphi}{\sqrt{1 - \frac{v^2}{c^2}}}$$

- longitudinal motion combines the ordinary Doppler factor with a relativistic correction
- in the transverse case, $\cos\varphi = 0$:

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The transverse component has no analogue in pre-relativistic wave theory.

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Stark and Einstein: Transverse Doppler Effect as a Test for Time Dilation

Stark's Second-Order Effect (Dynamical Explanation)

Stark's (1906) canal-ray experiments made fast-moving spectral emitters available (canal-ray ions emit sharp line spectra with characteristic frequencies):

- longitudinal observations show the ordinary first-order Doppler effect, which receives a kinematical explanation:

$$\frac{\Delta\lambda}{\lambda} \sim \pm\frac{v}{c}$$

- transverse observations suggest a direction-independent, second-order effect:

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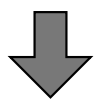
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Einstein's 1907 Kinematical Explanation

Einstein (1907) reinterpreted the effect as a test of **time dilation**:

- Spectral identity at rest and in motion: the ion's intrinsic frequency ν_0 is fixed by the nature of the ion, that is, by its spectral identity.
- Transverse arrangement: the ordinary longitudinal Doppler effect is eliminated.
- The remaining frequency shift follows from time dilation alone $\Delta t = \gamma \Delta t'$.

$$\nu = \frac{\nu'}{\sqrt{1 - \frac{v^2}{c^2}}},$$

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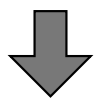
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Part IV

Einstein's 1908 *Jahrbuch* Paper

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Apparent but Testable

- **Stark**: frequency contraction: the intrinsic oscillation frequency ν_0 would be physically changed by the motion through the ether
  - a reduced number of oscillations N would occur in the same time interval
- **Einstein**: time dilation: the intrinsic oscillation frequency ν_0 is the same and the reduction disappears for a spectrograph co-moving with the ion
  - the same number of oscillations N is assigned a longer coordinate-time interval by a non-co-moving observer

$$\nu = \frac{N}{\Delta t} = \frac{N}{\gamma \Delta t'} = \frac{\nu_0}{\gamma} = \nu_0 \sqrt{1 - \frac{v^2}{c^2}}.$$

empirically testable: the difference in temporal rate is manifested as a difference in the wavelength detected by a spectrograph ($\lambda = c/\nu$)

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The formula $\nu = \nu_0 \sqrt{1 - \frac{v^2}{c^2}}$ admits of a very interesting application. Mr. J. Stark showed in the previous year that the ions forming canal rays emit line spectra, by observing a displacement of spectral lines that is to be interpreted as a Doppler effect. Since the oscillation process that corresponds to a spectral line is to be considered an intra-atomic process whose frequency is determined by the ion alone, we may consider such an ion as a clock of a certain frequency ν_0, which can be determined, for example, by investigating the light emitted by identically constituted ions which are at rest relative to the observer. The above consideration shows, then, that the effect of motion on the light frequency that is to be ascertained by the observer is not completely given by the [longitudinal] Doppler effect. The motion also reduces the (apparent) proper frequency of the emitting ions in accordance with the relation given above.

”

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- genuine physical effect: it would not be expected if the classical theory held

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- apparent: the star's actual position remains unchanged
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Part V

Ritz: Transverse Doppler Effect as *Experimentum Crucis*

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> According to the Lorentz–Einstein theory of relativity, the wavelength emitted by a moving atom must change not only in the direction of motion in accordance with the Doppler principle; when observed perpendicular to the direction of the velocity, there must also occur a red shift of magnitude $\frac{1}{2}\left(\frac{v}{c}\right)^2 \lambda$ ($c =$ speed of light) [. . .]
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> If the effect exists, then it is the end of our universal time, of the parallelogram of velocities, and of the whole of kinematics. I hope the effect does not exist–that would be much nicer. But since this is a genuine *experimentum crucis*, and since you may perhaps, despite the great difficulty, find a way to realize the matter, I wished to communicate it to you.

Ritz to Paschen, 14-06-1908

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Real and Apparent

- **1910–1911**: length contraction is ‘apparent’, since it is a coordinate effect, but ‘real’ since it is empirically testable:
  - stresses in the rotating disk
- **1910–1911**: time dilation is ‘apparent’, since it is a coordinate effect, but ‘real’, since it is empirically testable:
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> “It is real [*wirklich*], i.e., measurable with rods and clocks, and at the same time apparent [*scheinbar*] to the extent that it is not present for the co-moving observers”
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Conclusion

Argument Reconstructed

1. **Physical premises**
   - Spectral identity at rest: ions of the same species have the same intrinsic frequency ν_0.
   - Spectral identity under uniform motion: uniform translational motion does not permanently alter the internal oscillatory process.
2. **Experimental restriction**: transverse configuration: longitudinal Doppler contributions are excluded by the experimental arrangement.
3. **Prediction**: a residual shift remains:

$$\nu = \gamma^{-1}\nu_0.$$

4. **Kinematical Explanation**: the same N oscillations are assigned different coordinate-time intervals:

$$\Delta t = \gamma \Delta t'.$$

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Objection: Does not Einstein claim that Clocks Need Dynamics?

Ives: dynamical explanation of frequency change ⇒ neo-Lorentzian approach

Einstein: dynamical explanation of frequency invariance ⇒ kinematical approach

dynamical approach?

Dynamics explains the identity of clocks;
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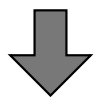
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- **provisionally**: Lorentz transformations are tested separately from dynamical laws using rods and clocks (modular confirmation).
- **as a matter of principle**: rods and clocks are described by dynamical laws invariant with respect to Lorentz transformations (holistic confirmation)
  - A theory supplying oscillatory processes characterized by an invariant period from constants of the theory ($\nu_C = \frac{mc^2}{h}$)
  - If the theory were Lorentz invariant, such solutions would recur in all inertial frames with the same frequency ($\nu_C = N/\Delta t'$)
  - The transverse Doppler effect is expected as a purely coordinate effect, while the invariance of ν_C is secured

special relativity explains not by finding a specific Lorentz-invariant theory of matter, but by requiring that any theory of matter is Lorentz invariant (Lange 2016)

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References I

 Brown, Harvey R. (2005). *Physical Relativity. Space-time Structure from a Dynamical Perspective*. Oxford: Clarendon.

 Brown, Harvey R. and Oliver Pooley (2006). “Minkowski Space-Time. A Glorious Non-entity”. In: *The Ontology of Spacetime*. Ed. by Dennis Dieks. Vol. 1. 2 vols. Philosophy and foundations of physics. Amsterdam: Elsevier, 67–89.

 Brown, Harvey R. and James Read (2022). “The Dynamical Approach to Spacetime Theories”. In: *The Routledge Companion to Philosophy of Physics*. Ed. by Eleanor Knox and Alastair Wilson. London, UK: Routledge, 70–85.

 Einstein, Albert (Mar. 1907). “Über die Möglichkeit einer neuen Prüfung des Relativitätsprinzips”. In: *Annalen der Physik*. 4th ser. 23, 197–198.

 Giovanelli, Marco (2014). “‘But One Must Not Legalize the Mentioned Sin. Phenomenological vs. Dynamical Treatments of Rods and Clocks in Einstein’s Thought”. In: *Studies in History and Philosophy of Science. Part B: Studies in History and Philosophy of Modern Physics* 48, 20–44.

References II

Giovanelli, Marco (2023). “Reality and Appearance. Einstein and the Early Debate on Reality of Length Contraction”. In: *European Journal for Philosophy of Science* 13 4.

— (2026). “Is Time Dilation Real? Einstein and the Transverse Doppler Effect”. In: *https://philsci-archive.pitt.edu/29245/1/EinsteinTDE.pdf*.

Janssen, Michel (2009). “Drawing the Line between Kinematics and Dynamics in Special Relativity”. In: *Studies in History and Philosophy of Science. Part B: Studies in History and Philosophy of Modern Physics* 40 1, 26–52.

Lange, Marc (Nov. 2016). *Because without Cause. Non-causal Explanations in Science and Mathematics*. New York: Oxford University Press.

Norton, John D. (2008). “Why Constructive Relativity Fails”. In: *The British Journal for the Philosophy of Science* 59 4, 821–834.

Stark, Johannes (1906). “Über die Lichtemission der Kanalstrahlen in Wasserstoff”. In: *Annalen der Physik* 326 13, 401–456.

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