



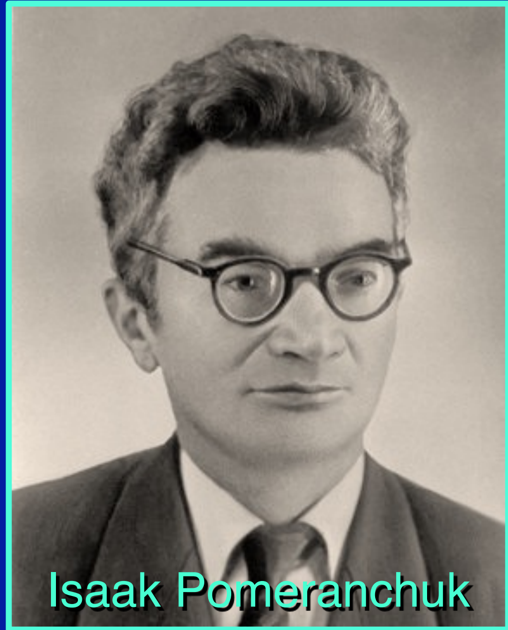


# Synchrotron Radiation and Relativity: 50 Years of Misunderstandings

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# Common mistakes:

due to time dilation effects as we shift frames, the particle will cross a factor of $\gamma$ more magnetic field lines per second than in the lab frame, effectively increasing the field by a factor of $\gamma$. Thus in the non-relativistic frame we find the frequency of emission to be:

$$\nu = \gamma \frac{eB}{mc} \tag{6.5}$$

The relativistic Doppler effect is different from the non-relativistic Doppler effect as the equations include the time dilation effect of special relativity and do not involve the medium of propagation as a reference point. They describe the total difference in observed frequencies and possess the required Lorentz symmetry.

Wikipedia, advanced articles, textbooks: the same misunderstandings everywhere!

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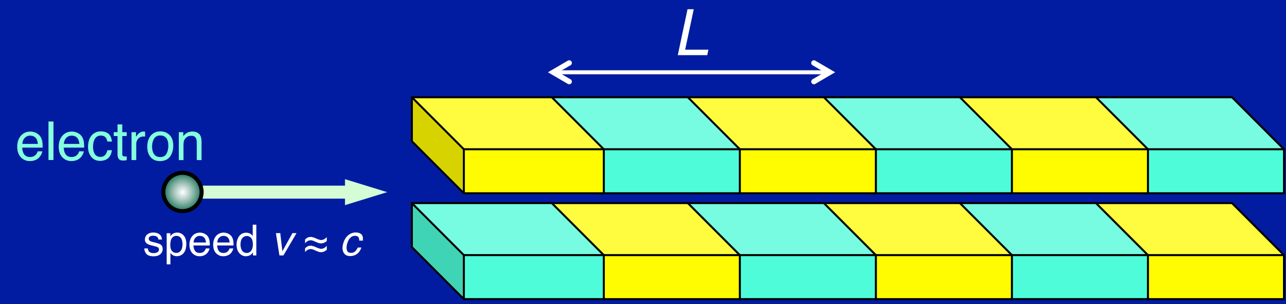
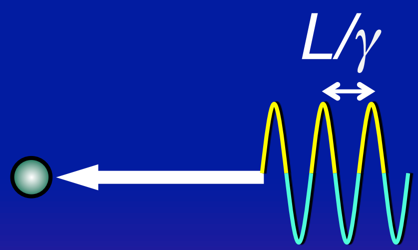
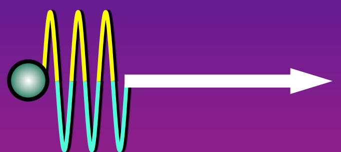
# Example: an "undulator", a magnet array of period *L* inserted in an accelerator




The electron "sees" the undulator as an electromagnetic "wave" moving with speed $-v \approx -c$




Relativity (Lorentz transform) adds to the transverse magnetic field a transverse electric field, creating the "wave", and shrinks the wavelength to $\approx L/\gamma$ (Lorentz contraction)



The electron backscatters this "wave", producing "synchrotron radiation"; in the laboratory, the wavelength is Doppler shifted to $\approx (L/\gamma)/(2\gamma) = L/(2\gamma^2)$

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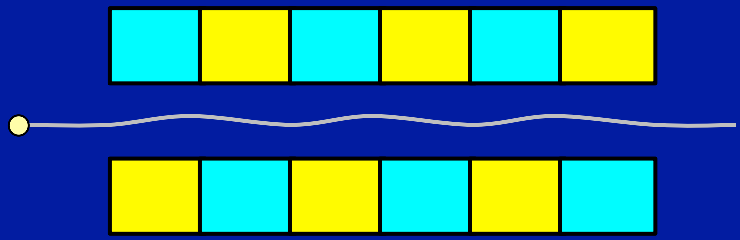
# A different, very frequent interpretation:



The electron in the laboratory frame oscillates with a time period $\approx L/c$

The time intervals in the electron frame, when measured in the laboratory frame, are subject to the <u>relativistic time dilation</u> and are multiplied by $\gamma$. Reciprocally, the period in the electron frame must be divided by $\gamma$ and becomes $\approx (L/c)/\gamma$

The emitted wavelength in the electron frame is $c\,[(L/c)/\gamma] \approx L/\gamma$

…hence, the wavelength becomes $L/\gamma$ because of the <u>time dilation</u>

…well spoken, but <u>WRONG!</u>

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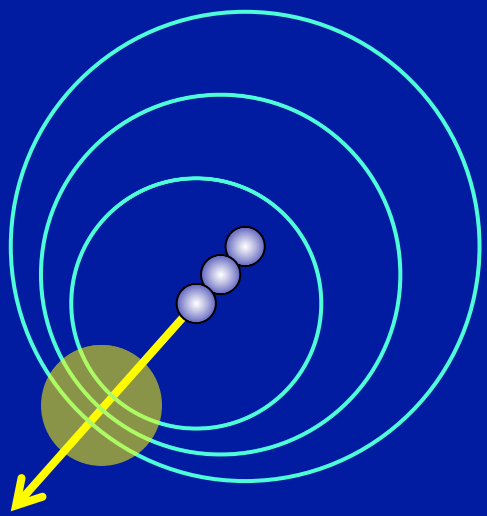
# A similar, frequent misconception in the derivation of the relativistic Doppler effect:



Longitudinal non-relativistic Doppler frequency shift, e.g., for sound:
$\nu = \nu'/(1 - v/c)$ , where $c$ is the wave speed

Correction for the relativistic time dilation -- the measured time intervals are longer by a factor $\gamma$ in the laboratory frame than in the source frame, so the frequencies are smaller by the same factor in the laboratory frame than in the electron frame:

$$\nu = \nu'/[\gamma(1 - v/c)] = \nu'(1 - v^2/c^2)^{1/2}/(1 - v/c) = \nu'[(1 + v/c)/(1 - v/c)]^{1/2}$$
$$= \nu'(1 + v/c)/(1 - v^2/c^2)^{1/2} \approx 2\gamma\nu'$$ -- therefore: $\lambda \approx \lambda'/(2\gamma)$

...hence, the Doppler effect is caused by the time dilation

…well spoken, but WRONG AGAIN!

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# What is wrong with the "time-dilation" interpretation of the Doppler effect?

"*To understand the absurdity of claims that the SR-Doppler [Special Relativity-Doppler] effect is created at the source due to time dilation, the reader should consider not two but three different observers, e.g. two different travelers and the laboratory source. There are three different relative velocities. There are three different SR-Doppler shifts observed that must be relative and reciprocal. The only way that this can be true is that the Doppler shift is created by the method of observation and not by state of motion of the source*".

J. Rafelski, "*Relativity Matters*", 2017

# Actually, the relativistic Doppler effect is easily explained without time dilation

Consider an electromagnetic wave traveling along the $z$-axis:
$E = E_o \sin[2\pi\nu(z/c - t)]$ in the laboratory frame
$E' = E_o' \sin[2\pi\nu'(z'/c - t')]$ in the electron frame

The phase arguments $2\pi\nu(z/c - t)$ and $2\pi\nu'(z'/c - t')$ of these waves must be Lorentz-invariant (otherwise one could violate relativity by using phase-related phenomena like interference to reveal the relative motion of two inertial reference frames): $\nu(z/c - t) = \nu'(z'/c - t')$

Using the Lorentz transformations $z' = \gamma(z - vt)$ and $t' = \gamma(t - vz/c^2)$, this gives $\nu(z/c - t) = \nu'[\gamma(z - vt)/c - \gamma(t - vz/c^2)]$, hence
$\nu(z/c - t) = \nu'\gamma(z/c - t)(1 + v/c)$, and
$\nu = \nu'\gamma(1 + v/c) = \nu'[(1 + v/c)/(1 - v/c)]^{1/2} \approx 2\gamma\nu'$

**…the same Doppler equation as above, but correctly derived without invoking time dilation!**

# And what is wrong about attributing to time dilation the emitted wavelengths in the electron reference frame?

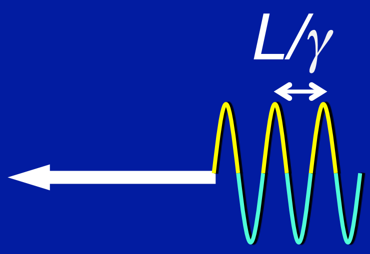
"*Light travels in space in a way that must be completely independent of the state of motion of the source; there cannot be an effect of motion of the source that can be ascribed to properties of emitted light*".

J. Rafelski, "*Relativity Matters*", 2017

"*an observer in the frame R' would not know the state of relative motion of the laboratory observer that will eventually detect the radiation – who may not even exist. Therefore, one cannot expect this relative state of motion to influence the emitted waves in R'*."

# Of course, one can avoid using time dilation when deriving the wavelength in the electron reference frame:

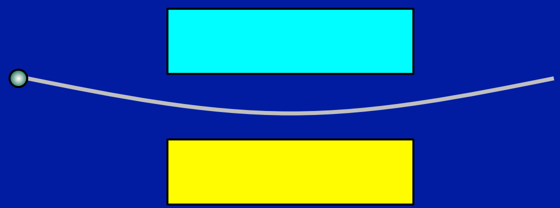
The electron "sees" the undulator as an electromagnetic "wave" moving with speed $-v \approx -c$




Relativity (Lorentz transform) adds to the transverse magnetic field a transverse electric field, creating the "wave", and shrinks the wavelength to $\approx L/\gamma$ (Lorentz contraction)

The only thing that matters is the Lorentz transformation of the magnetic field of the device that causes the emission of synchrotron radiation

# The same conclusion is valid for a bending magnet:



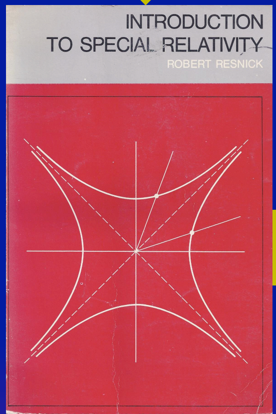
Classical physics: the magnetic force strength is $evB$, thus the acceleration is $evB/m_o$. The centripetal acceleration equals $\omega_c v$ , where $\omega_c$ is the cyclotron frequency. Thus, $\omega_c = eB/m_o$

Relativity: in the electron frame, the Lorentz transform adds to the magnetic field an electric field of strength $\gamma Bc$ -- so the force becomes $e\gamma Bc$. The acceleration $\omega_c' v \approx \omega_c' c$ gives $\omega_c' = \gamma eB/m_o$

Here again, the only thing that matters is the Lorentz transformation of the magnetic field of the device (the bending magnet), i.e., how the electron "sees" the device

# What caused the misconceptions?


50 years ago, a sentence in Max von Laue’s classical German text *Die Relativitätstheorie* was misinterpreted in Robert Resnick’s *Introduction to Special Relativity*: he misunderstood the presence of the $\gamma$-factor in both the time dilation and the Doppler effect as a direct cause-effect link



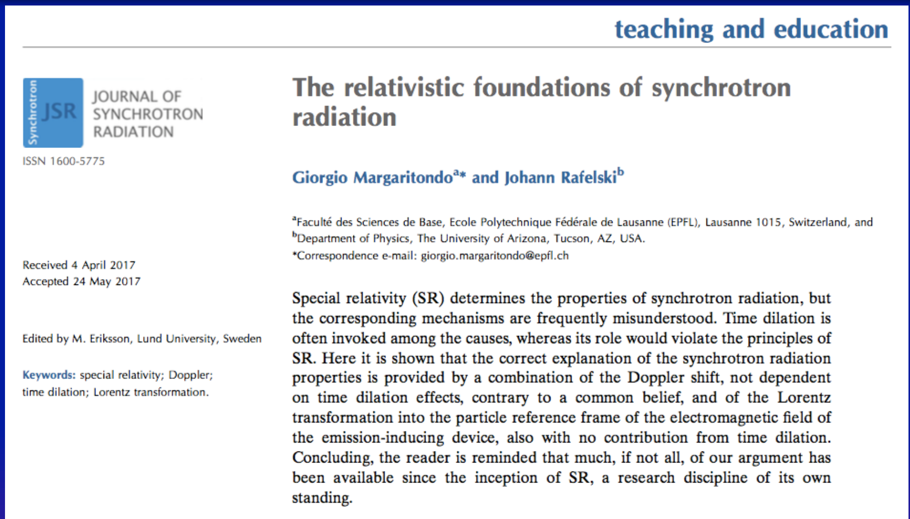


Subsequently, the mistake percolated into the popular “Resnick-Halliday-Krane” series of physics textbooks…

…and then into many articles and textbooks, publications on synchrotron radiation …and Wikipedia

# Conclusions:

Each synchrotron source emits a band around a central wavelength. The central wavelength always includes a factor $(\gamma)(2\gamma) = 2\gamma^2$ in the denominator, due to two relativistic effects: (1) the Lorentz transformation of the field of the emitting device, and (2) the relativistic Doppler shift



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**The relativistic foundations of synchrotron radiation**

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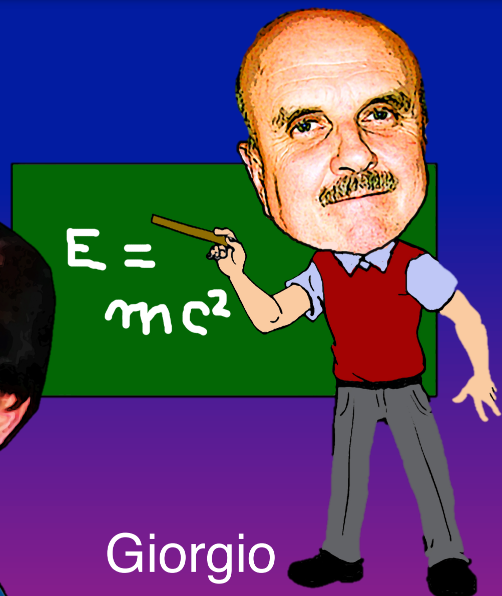
Keywords: special relativity; Doppler; time dilation; Lorentz transformation.

Special relativity (SR) determines the properties of synchrotron radiation, but the corresponding mechanisms are frequently misunderstood. Time dilation is often invoked among the causes, whereas its role would violate the principles of SR. Here it is shown that the correct explanation of the synchrotron radiation properties is provided by a combination of the Doppler shift, not dependent on time dilation effects, contrary to a common belief, and of the Lorentz transformation into the particle reference frame of the electromagnetic field of the emission-inducing device, also with no contribution from time dilation. Concluding, the reader is reminded that much, if not all, of our argument has been available since the inception of SR, a research discipline of its own standing.

Neither one of these effects should be confused with the relativistic time dilation, as it is often done

Jan Rafelski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finally, 112 years after Einstein's work, and 50 years after the misunderstandings first appeared, a correction... courtesy of the "old guard"

# …not the only propagating mistake in physics!

In 1905, Albert Einstein published a paper advancing the hypothesis that light energy is carried in discrete quantized packets to explain experimental data from the photoelectric effect.

(Wikipedia, again)

**HOW COULD HE? THE "EXPERIMENTAL DATA" DID NOT YET EXIST IN 1905, AND WERE OBTAINED ONLY A DECADE LATER BY ROBERT MILLIKAN (WHO DID NOT UNDERSTAND THEM)!**

Origin of the mistake: a misinterpretation of the vague and politically correct *laudatio* for Einstein's Nobel prize – "*for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect* "

# …can you identify which one is the wrong statement among the following?

"The research of the French scientist Lavoisier definitely established the existence of atoms: by the end of his life (1794), the notion was universally accepted in the scientific world"

"Mme. Curie was a very shy, respectable lady. After becoming a widow, her life was totally devoted to science and her husband's memory, in particular after her got her second Nobel prize and became a member of the French Science Academy"

"The American investments in the Manhattan project established the historical record of research expenditures by a country with respect to its GNP"

"The first proposal for a fully dedicated synchrotron source was so convincing that it was fully funded without refereeing"

"When synchrotron emission was first observed, the scientists immediately recognized its nature"