We love physics

Doppler Effect

Explanation and real life applications

Did you ever hear “ni-NOO-ni-NOO” when an ambulance went past you…?

—yifeiyu

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01. Background information

So how did the Doppler effect come into existence?

Key Scientists involved

Christian Andreas Doppler

- Austrian physicist that described this phenomenon in 1842

Christophorus Buys Ballot

- Dutch scientist that experimentally confirms the phenomenon in 1845

History of discovery

- Christian Doppler first presented his principle in 1842 in his paper titled "On the Colored Light of the Double Stars and Certain Other Stars of the Heavens." His work initially focused on the frequency changes in sound waves, but the principles he described were later found to apply to all types of waves.
- The Doppler Effect was experimentally confirmed in 1845 by the Dutch scientist Christophorus Buys Ballot. Using a group of musicians playing trumpets on a moving train, Buys Ballot demonstrated the change in pitch predicted by Doppler. This experiment was one of the earliest confirmations of Doppler's theory.
- Hippolyte Fizeau discovered independently the same phenomenon on electromagnetic waves in 1848.
- In Britain, John Scott Russell made an experimental study of the Doppler effect (1848)

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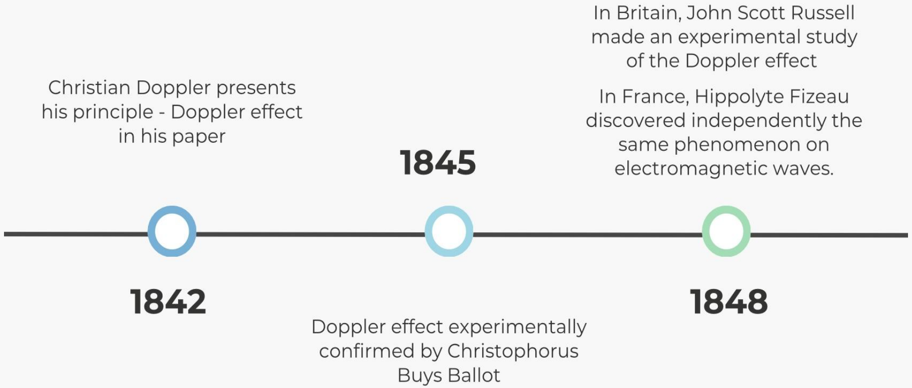


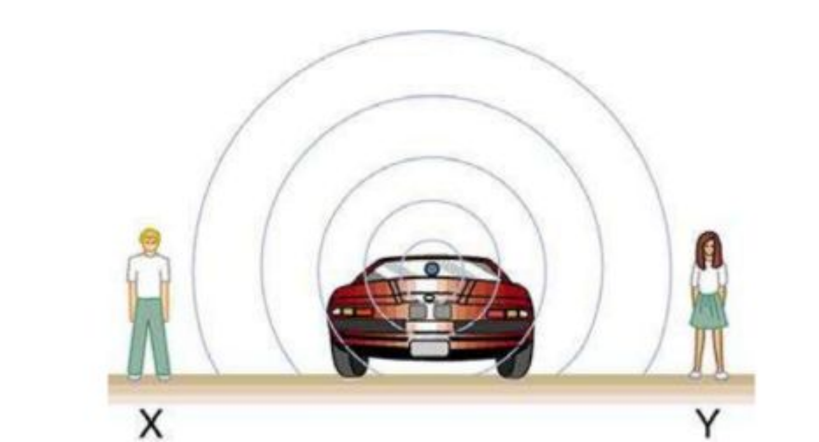
Literature review

How does Doppler Effect happen?

The circles represent wavefronts emitted by the car's horn.

Each wavefront spreads out **spherically** from the point where the sound was emitted.

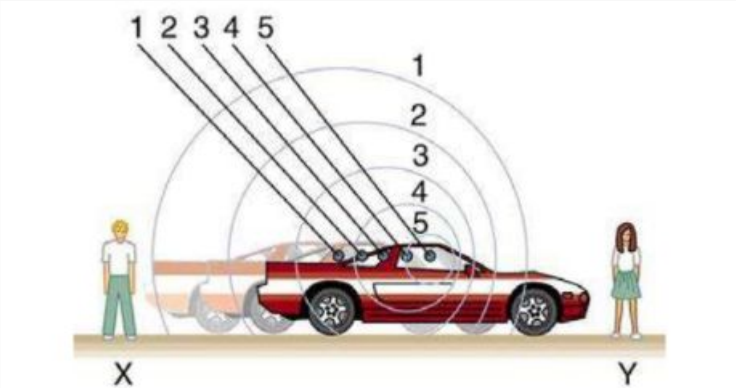
If the source is stationary, then all of the spheres representing the wavefronts are centered on the same point, and stationary observers on either side detect the same wavelength and frequency as emitted by the source.



How does Doppler Effect happen?

However, if the source is moving towards the observer, each wavefront moves outward in a sphere from the point where it was emitted, but **the point of emission moves as well**.

This causes the wavefronts to be c**loser together on one side** and **further apart** on the other. As a result, the wavelength is **shorter** in the direction the source is moving and **longer** in the opposite direction.

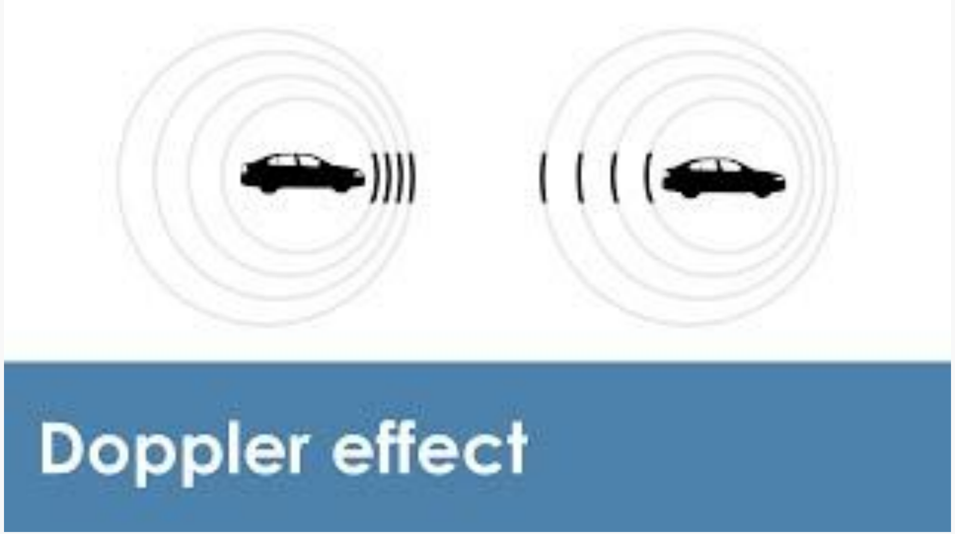


Sounds emitted by a source moving to the right spread out from the points at which they were emitted.

Source moving towards a stationary observer

$v = f\lambda$

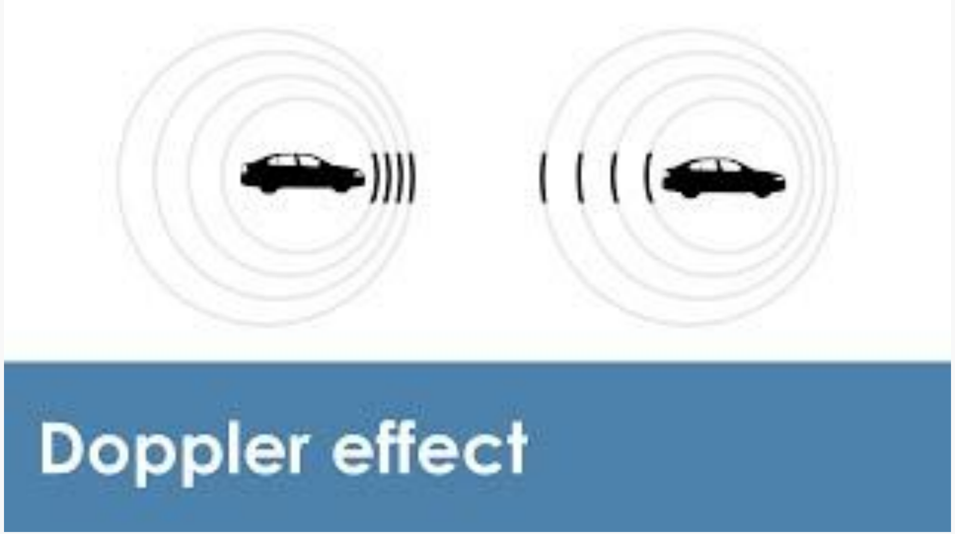
The **wavelength is reduced** and consequently, the **frequency is increased** in the direction of motion, so that the observer hears a higher-pitch sound.



Source moving away from a stationary observer

$$v = f\lambda$$

The **wavelength is increased** and consequently, the **frequency is decreased** in the direction of motion, so that the observer hears a lower-pitch sound.



Equations

$$f_o = f_s\left(\frac{v \pm v_o}{v \pm v_s}\right)$$

f_o = The observer's frequency of sound
v = Sound waves' speed
v_o = The velocity of the observer
v_s = Velocity of the source
f_s = Sound waves' actual frequency

Use + for V_o *if the observer moves toward the source*
Use - for V_o *if the observer moves away from the source*
Use - for V_s *if the source moves* towards *the observer*
Use + for V_s *if the source moves away from the observer*

Applications

Redshift, Sonic boom

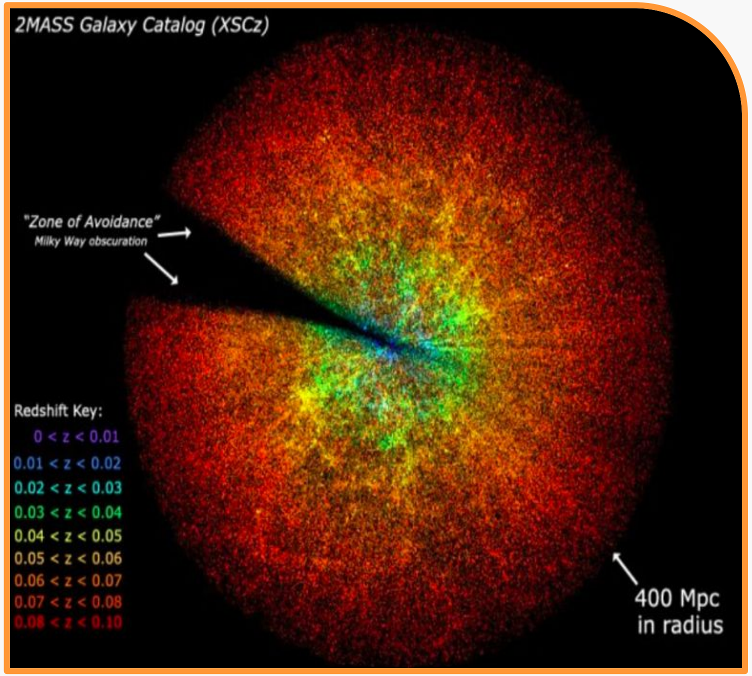
Redshift-Basic concepts

Central idea

From earth, every direction that we look into space the galaxies seem to be moving further and further away from us.

In other words, the universe is expanding!

The main evidence for this is the red shifting of light from distant galaxies.

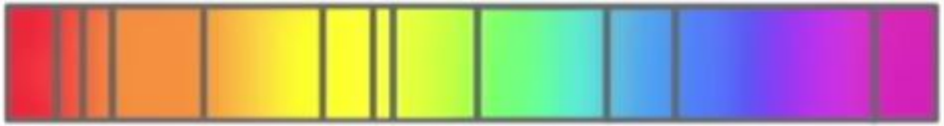


Redshift-Basic concepts

Absorption spectra

Longer wavelengths Shorter wavelengths

- Galaxies give off light that travels to Earth. On the way, some wavelengths get absorbed by chemicals in the star's atmosphere, creating **dark lines** in the spectrum (absorption lines).

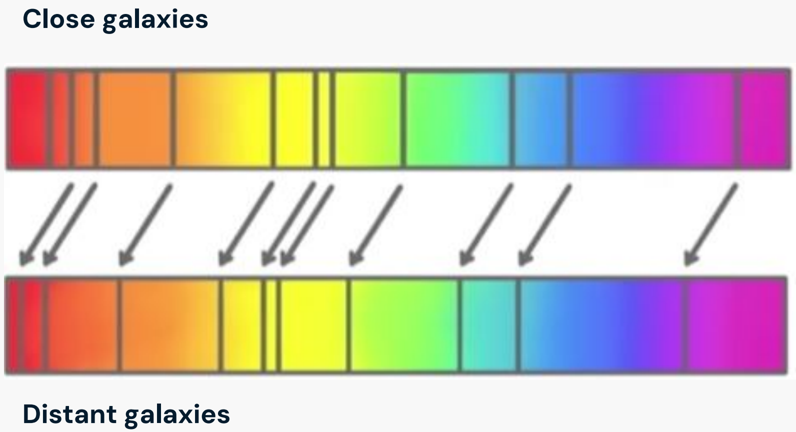


Longer wavelengths Shorter wavelengths

Redshift-Basic concepts

Absorption spectra

- The spectra of distant galaxies show the **same pattern** of lines as nearby galaxies, but all **shifted towards the red end**.
- This shift is called **redshift**
    - This happens because the light waves are stretched as they travel to Earth, making the wavelengths (and the gaps between the lines) longer and light to appear redder.



Redshift-Doppler effect

Basic concept

- The Doppler effect provides the link between measured spectral shifts and motion.
- Definition of red shift (z):
  - Displacement of the spectrum of an astronomical object toward longer (red) wavelengths.
- Basic equation:

$$z = \frac{(\lambda_{obs} - \lambda_{em})}{\lambda_{em}} = \frac{\lambda_{obs}}{\lambda_{em}} - 1$$

λ_{em} = emitted/rest wavelength of light

λ_{obs} = observed wavelength

$z>0$ means redshift (object moving away / space expanding).

$z<0$ means blueshift (object moving closer).

Redshift-Doppler effect

Non-relativistic Doppler Approximation

- Used where objects are moving with small velocities that is much less than the speed of light, for example most stars in the milky way

$$z \approx \frac{v}{c}$$

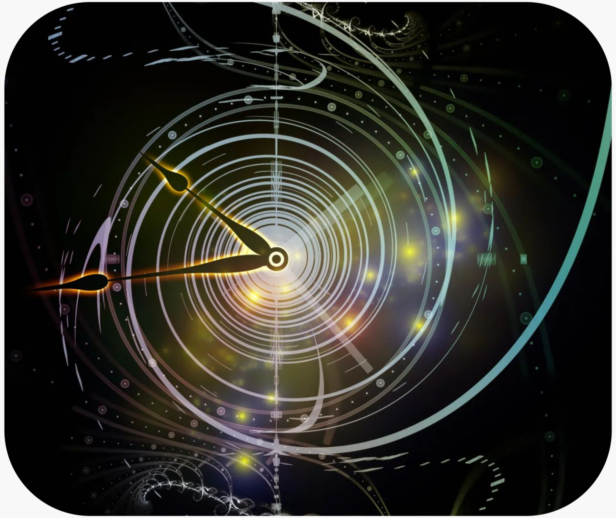
v = velocity of source relative to the observer

c = speed of light

Used where $v \ll c$

Redshift-Doppler effect

Relativistic Doppler Formula



- Used where the object is moving at high velocities (close to the speed of light). Such objects will experience deviation from the non-relativistic doppler formula due to time dilation and special relativity.
  - Special relativity indicates that, for an observer in an inertial frame of reference, a clock that is moving relative to the observer will be measured to tick more slowly than a clock at rest in the observer's frame of reference. The faster the relative velocity, the greater the time dilation between them, with time slowing to a stop as one clock approaches the speed of light, c.

Redshift-Doppler effect

Relativistic Doppler Formula

- The deviations caused by time dilation and special relativity could be corrected for by introducing the Lorentz factor γ into the Doppler formula (For motion solely in line of sight):

$$1 + z = \left(1 + \frac{v}{c}\right)\gamma.$$

  - The Lorentz factor γ is deduced via: $\gamma = 1/\sqrt{1 - \mathbf{v}^2/c^2}$

- The equation (For motion solely in line of sight) evolves to:

$$1 + z = \sqrt{\frac{1 + v/c}{1 - v/c}}$$

Redshift-Doppler effect

Relativistic Doppler Formula

- Since the Lorentz factor is dependent only on the magnitude of the velocity, the redshift associated with the relativistic correction is independent of the orientation of the source movement.
- The classical Doppler formula, however, hones different results for different orientations.
- If θ is the angle between the direction of relative motion and the direction of emission in the observer's frame (zero angle is directly away from the observer), the full form for the relativistic Doppler effect is:

$$1 + z = \frac{1 + v\cos(\theta)/c}{\sqrt{1 - v^2/c^2}}$$

What is sonic boom?

What happens to the sound produced by a moving source, such as a jet airplane, that approaches or even exceeds the speed of sound?

What is sonic boom?

F18 Hornet Sonic Boom
(happens around 18s)
(cover your ears)

Sonic Boom Explanation

Suppose a jet airplane is coming nearly straight at you, emitting a sound of frequency f_s

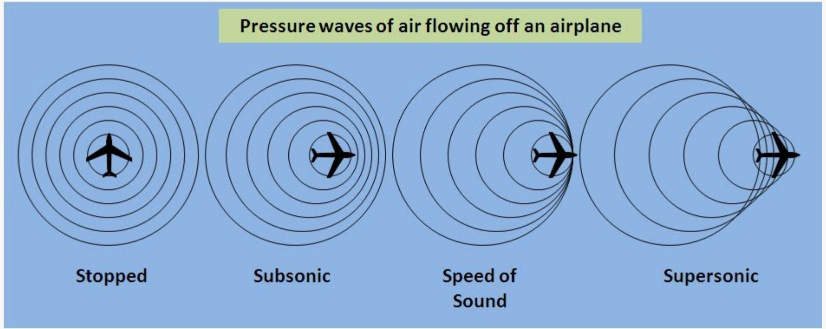
The greater the plane's speed v_s, the greater the Doppler shift and the greater the value observed for v_o

As v_s approaches the speed of sound, f_o approaches infinity, because the denominator in $f_o = f_s \left(\frac{v \pm v_o}{v \pm v_s} \right)$ approaches zero.

Sonic Boom Explanation

At the speed of sound, this result means that in front of the source, each successive wave is **superimposed** on the previous one
Since the source moves forward at the speed of sound, the observer gets them all at the same instant, and so the **frequency is infinite**.

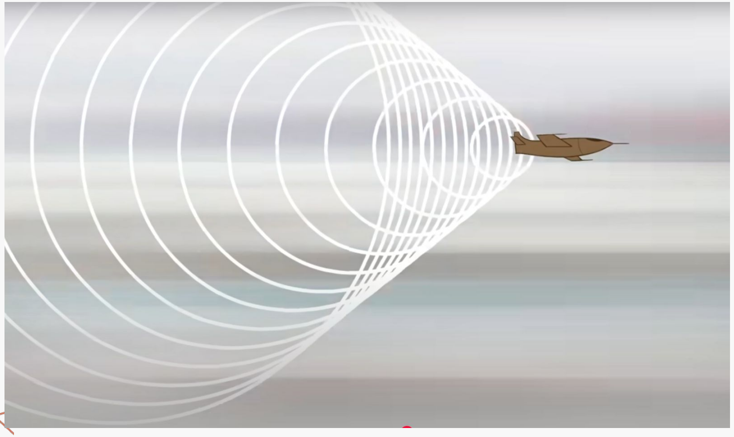
If the source exceeds the speed of sound, no sound is received by the observer until the source has passed, so that the sounds from the approaching source are mixed with those from it when receding. This mixing appears messy, but something interesting happens—a sonic boom is created.

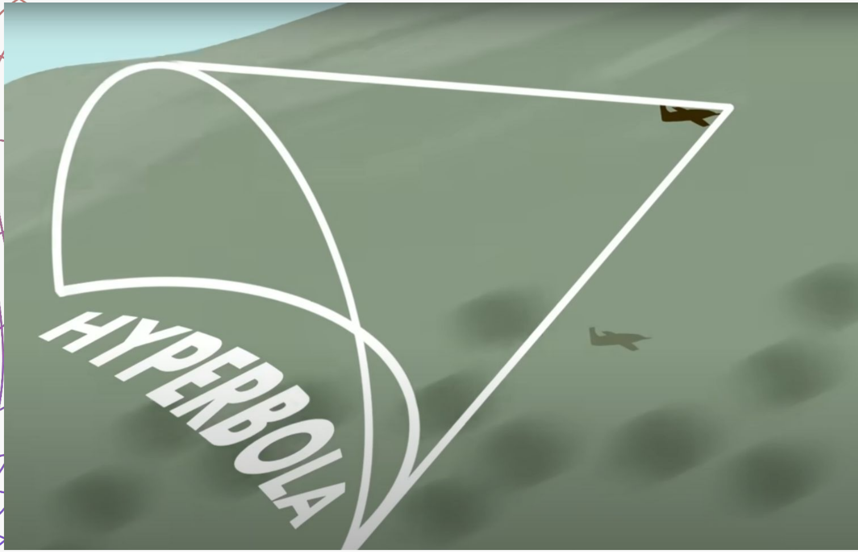


Mach Cone

The shock wave forms a “**cone**” of pressurised or built-up air molecules, which move outward and rearward in all directions and extend all the way to the ground. As this cone spreads across the landscape along the flight path, it creates a **continuous sonic boom along the full width of the cone’s base**. The sharp release of pressure, after the buildup by the shock wave, is heard as the sonic boom.

When the Mach Cone meets the ground, it creates a hyperbola ->
This makes it possible to determine the area affected by a sonic boom



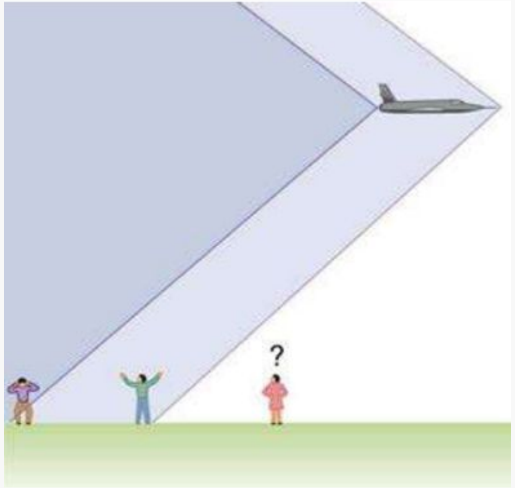


Sonic Boom by Aircraft

An aircraft creates two sonic booms, one from its nose and one from its tail.

First Boom — from the nose
As the nose of the aircraft punches through the air, it compresses air molecules extremely quickly, forming the first shock wave.
Second Boom — from the tail
The tail of the aircraft also disrupts the air and creates a second shock wave, following behind the first. The time delay between the two depends on the length of the aircraft and the speed of sound.

If the aircraft flies close by at low altitude, pressures in the sonic boom can be destructive and break windows



You will hear **two quick, explosive booms** in succession—**boom–boom**—as the shock waves from the **nose** and **tail** reach you

Thank you!!!

Thank you thank you thank you thank you thank you thank you thank you thank you thank you thank you thank you thank you thank you thank you thank you thank you

Citations

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$$\Delta t_{\text{emit, our frame}} = \gamma T_e, \quad \gamma = \frac{1}{\sqrt{1-\beta^2}}.$$

2. **Extra travel-time because the source has moved away**
   By the time the next crest is emitted, the source is farther by $v\,\gamma T_e$. That adds propagation time $(v\,\gamma T_e)/c = \beta\,\gamma T_e$.
3. **Arrival time between crests (what sets observed frequency)**

$$\Delta t_{\text{arr}} = \gamma T_e(1+\beta).$$

So

$$f_{\text{obs}} = \frac{1}{\Delta t_{\text{arr}}} = \frac{1/T_e}{\gamma(1+\beta)} = \frac{f_e}{\gamma(1+\beta)}.$$

4. **Algebra to the symmetric form**
   Use $\gamma = 1/\sqrt{1-\beta^2}$:

$$\frac{1}{\gamma(1+\beta)} = \frac{\sqrt{1-\beta^2}}{1+\beta} = \sqrt{\frac{1-\beta}{1+\beta}}.$$

Hence

$$\frac{f_{\text{obs}}}{f_e} = \sqrt{\frac{1-\beta}{1+\beta}}.$$

5. **Convert to wavelength & redshift**
   Since $\lambda f = c$,

$$\frac{\lambda_{\text{obs}}}{\lambda_e} = \sqrt{\frac{1+\beta}{1-\beta}} = 1+z.$$

So the **exact** special-relativistic result is:

$$\boxed{1+z = \sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}}}.$$

- If you square both sides, you'll see the version **without the square root**:

$$(1+z)^2 = \frac{1+\frac{v}{c}}{\cdots}$$