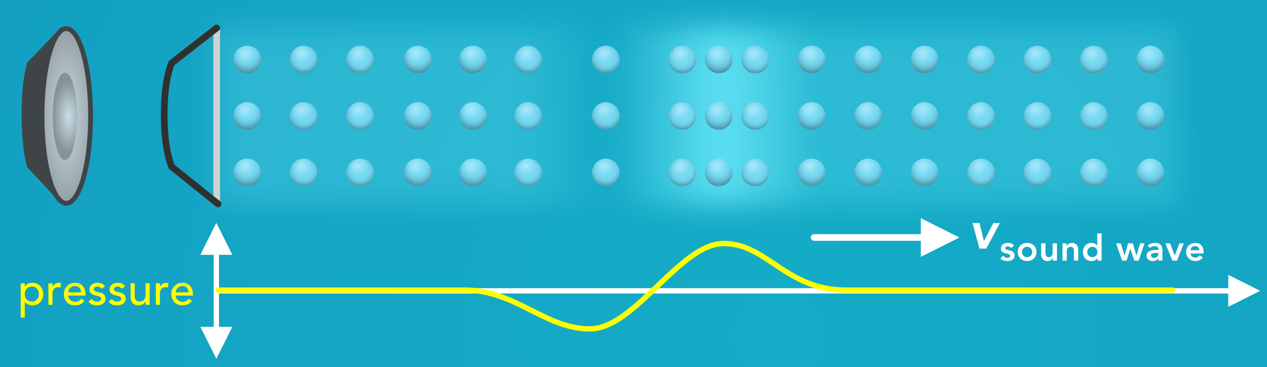
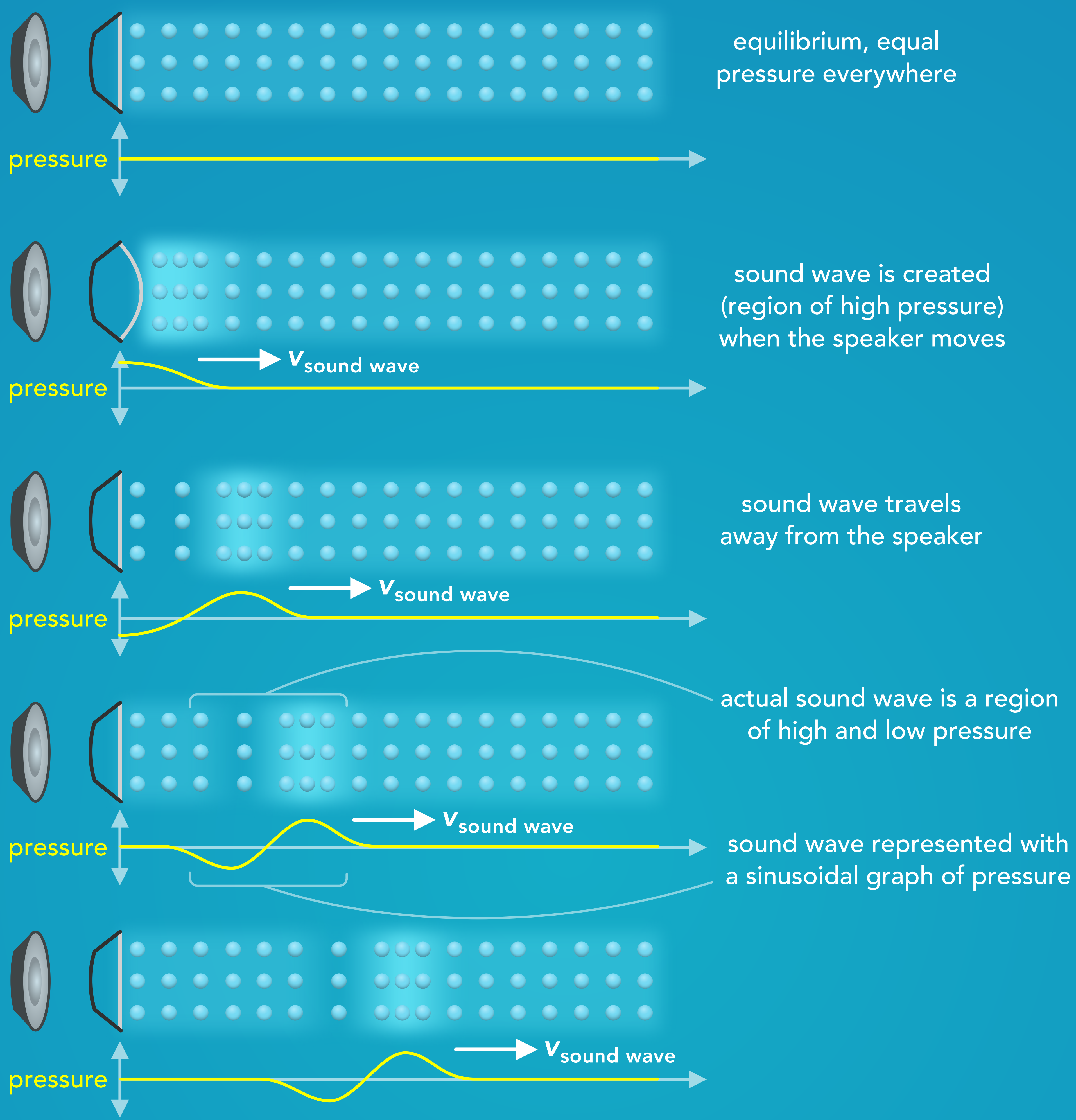
SOUND

Sound Waves

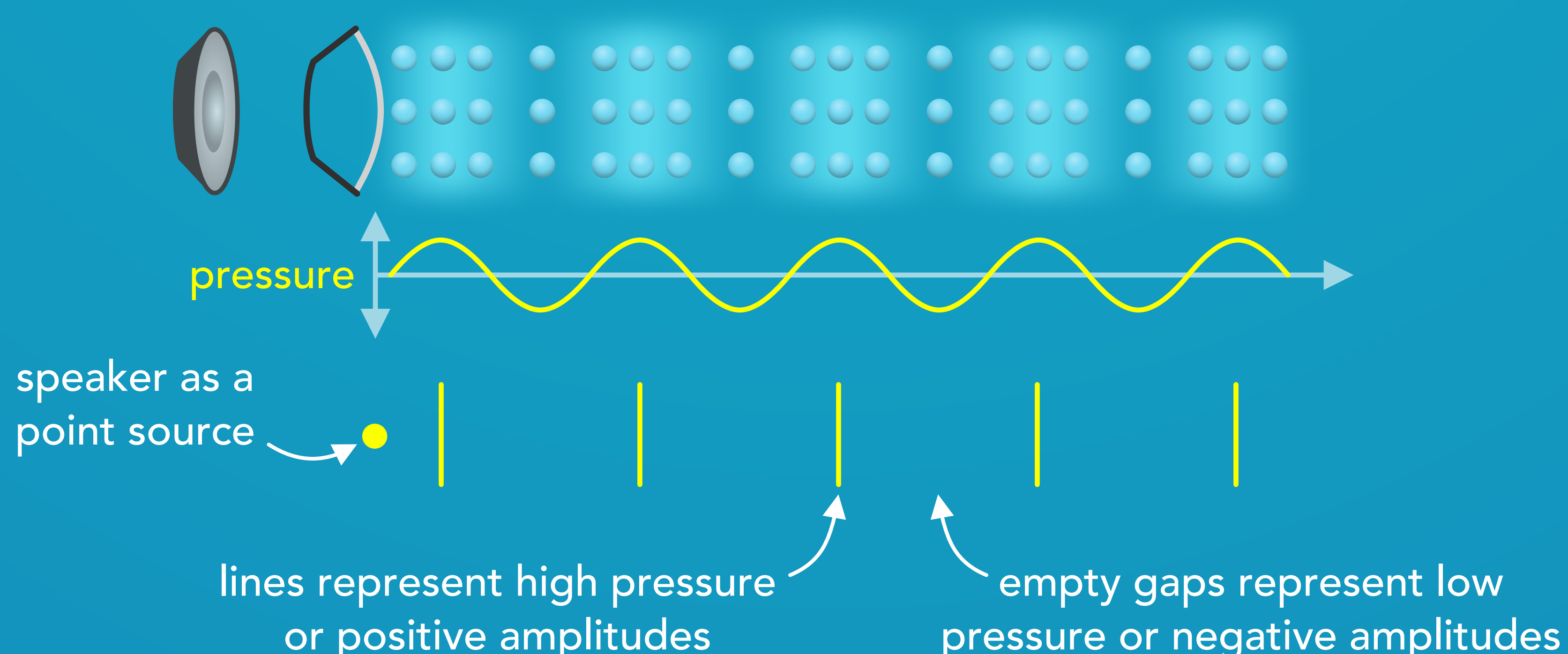
- **Sound waves** are longitudinal pressure waves where regions of high and low air pressure move as a wave.
- A volume of air consists of empty space and gas molecules (oxygen, nitrogren and more) which are constantly moving around. When the air is in a normal equilibrium state (no sound waves or other disturbances are present) the gas molecules are moving around but they are evenly spaced and the air pressure is the same everywhere.
- If the gas molecules get closer to each other there are more gas molecules per volume of space and the pressure in that region is higher. If the gas molecules get farther from each other there are less gas molecules per volume of space and the pressure in that region is lower.
- If something causes a disturbance such as a moving object or a speaker playing music, the gas molecules directly next to the moving surface will also move, either towards or away from the neighboring gas molecules. This creates a region of high or low pressure. Soon after, the gas molecules (and their neighbors) will move from a high pressure region towards a low pressure region to reach equilibrium pressure again. However, this causes a “chain reaction” of moving gas molecules, and the result is that the region of high and low pressure moves in one direction away from the source of the disturbance. This is a sound wave.
- A physical sound wave is a moving region (or many regions in a row) of high and low pressure, but sound waves (and other longitudinal waves) are often represented as a visual sinusoidal wave where the vertical axis represents the air pressure. This may look like a transverse wave but it’s just a representation of air pressure at each position.



A sound wave is a moving region of high pressure and low pressure

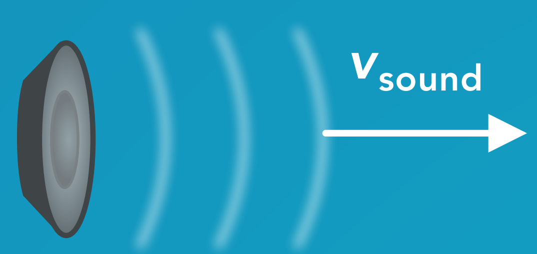


Repeating sound waves can be represented as lines called “wave fronts”, where the lines represent high pressure regions (positive amplitudes) and the empty gaps represent low pressure regions (negative amplitudes)



- The **speed** that a sound wave moves through a medium depends on several things. For a sound wave moving in a gas, the speed of sound depends on the temperature, the molar mass of the gas and the adiabatic index (also known as the heat capacity ratio) of the gas which is a number between 1 and 2 for most gases.

Constants		Unit	Name
R	8.3145	$\frac{J}{mol \cdot K}$	ideal gas constant



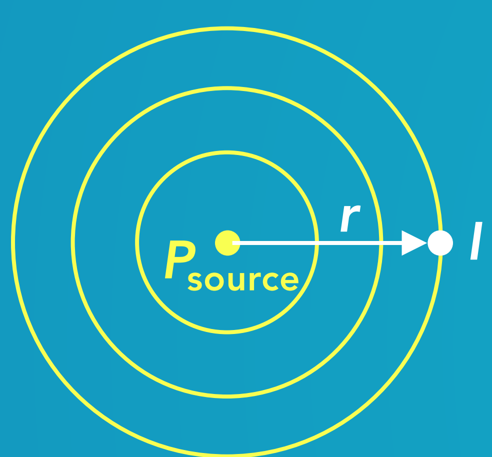
Speed of sound in a gas

$$v_{sound} = \sqrt{\frac{\gamma R T}{M}}$$

Variables		SI Unit
v	velocity	$\frac{m}{s}$
γ	adiabatic index	
T	temperature	K
M	molar mass	$\frac{kg}{mol}$

- As a circular sound wave moves away from a point source, the **intensity** or volume of the sound decreases.
- The **sound intensity level** is relationship between the sound intensity and the human threshold of hearing, and describes sound intensity in a way that's more relevant to the way humans perceive sound. Sound intensity level is measured in decibels (dB).

Constants		Unit	Name
I_0	1×10^{-12}	$\frac{W}{m^2}$	threshold of hearing



Sound intensity

$$I = \frac{P_{source}}{4\pi r^2}$$

Sound intensity level

$$\beta = (10\text{ dB})\log_{10}\left(\frac{I}{I_0}\right)$$

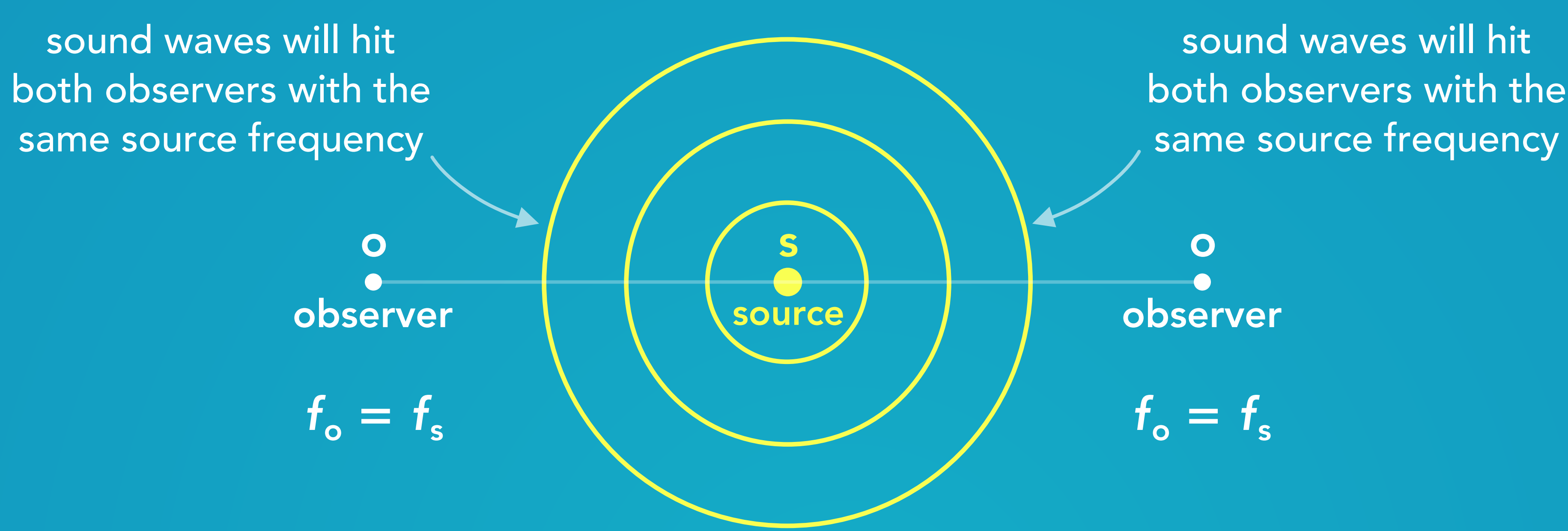
Variables		SI Unit
I	sound intensity	$\frac{W}{m^2}$
P	power	$\frac{J}{s}$
r	distance from source	m
β	sound intensity level	dB

Doppler Effect

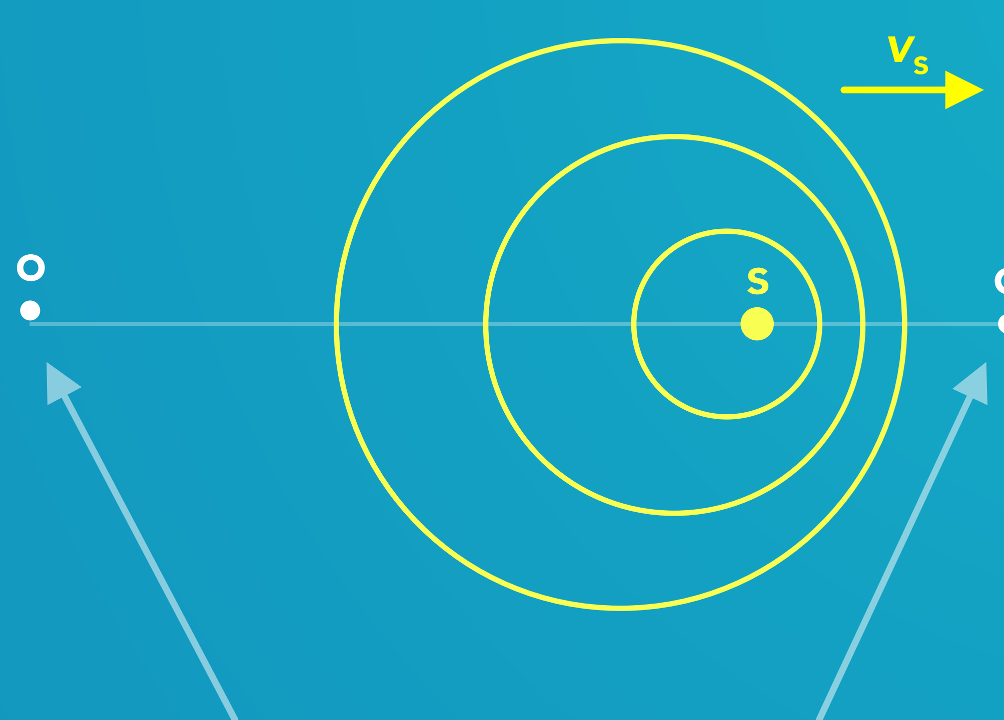
- When a sound source and an observer are moving relative to each other, the frequency that the observer hears is different than the true frequency of the sound source. The sound waves become compressed (closer together) or decompressed (farther apart) from the perspective of the observer which changes the wavelength and frequency.
- If the source and the observer are moving towards each other the observed frequency is higher. If the source and the observer are moving away from each other the observed frequency is lower.

Variables		SI Unit
f_s	source frequency	Hz
f_o	observed frequency	Hz
v_s	source speed	$\frac{m}{s}$
v_o	observer speed	$\frac{m}{s}$
v	speed of sound	$\frac{m}{s}$

Stationary source, stationary observers
(no doppler effect)



Moving source, stationary observers



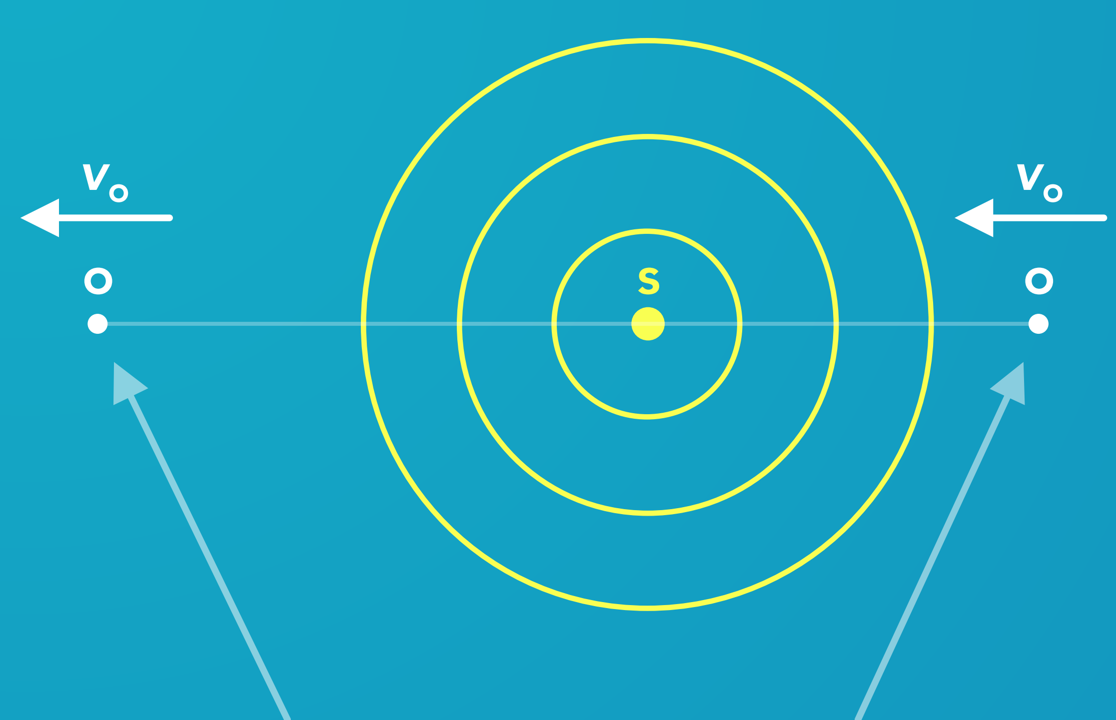
$$f_o = \frac{f_s}{1 + (v_s/v)}$$

Observed frequency, receding sound source

$$f_o = \frac{f_s}{1 - (v_s/v)}$$

Observed frequency, approaching sound source

Stationary source, moving observers



$$f_o = \left(1 - \frac{v_o}{v}\right) f_s$$

Observed frequency, receding observer

$$f_o = \left(1 + \frac{v_o}{v}\right) f_s$$

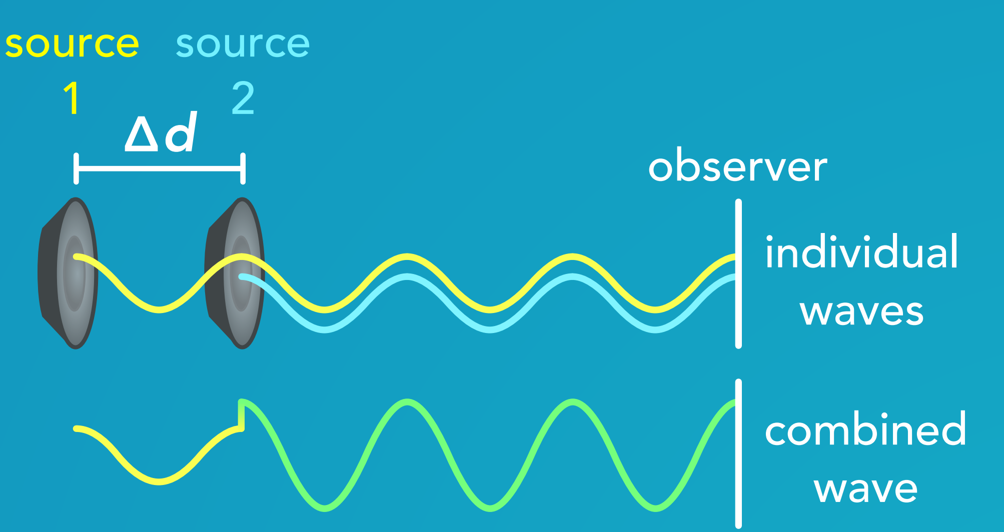
Observed frequency, approaching observer

Sound Wave Interference

- When multiple sound waves overlap (interfere), their values at every position are added together, resulting in a new wave. At every point:
  - If the values of each wave have the same sign (positive or negative) the result is **constructive interference** and the waves "build" on each other, creating a larger wave.
  - If the values of each wave have opposite signs, the result is **destructive interference** and the waves "subtract" from each other, creating a smaller wave (or no wave if they completely cancel out).

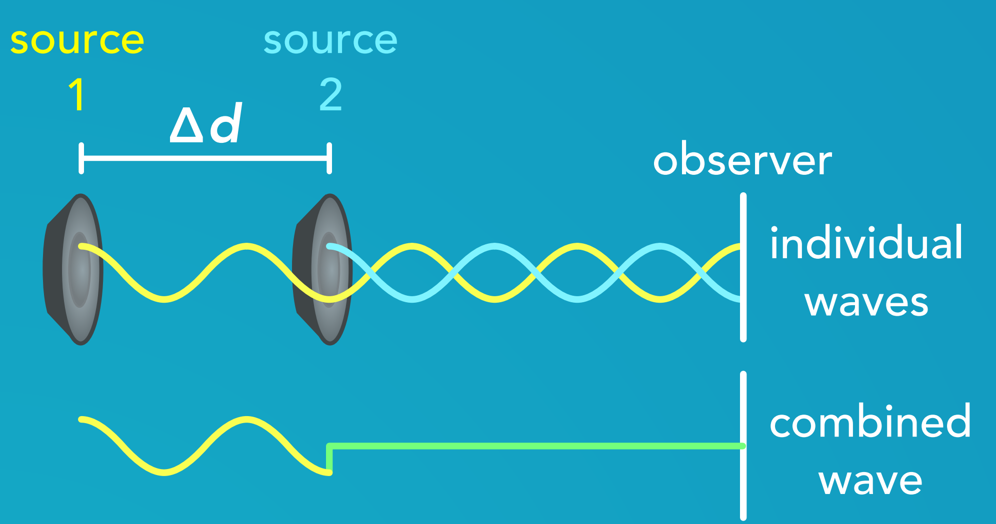
Variables		SI Unit
d	in-line path length	m
r	radial path length	m
λ	wavelength	m
m	number of wavelengths	

In-line sound wave interference



$$\Delta d = m\lambda \quad m = 0, 1, 2, \ldots$$

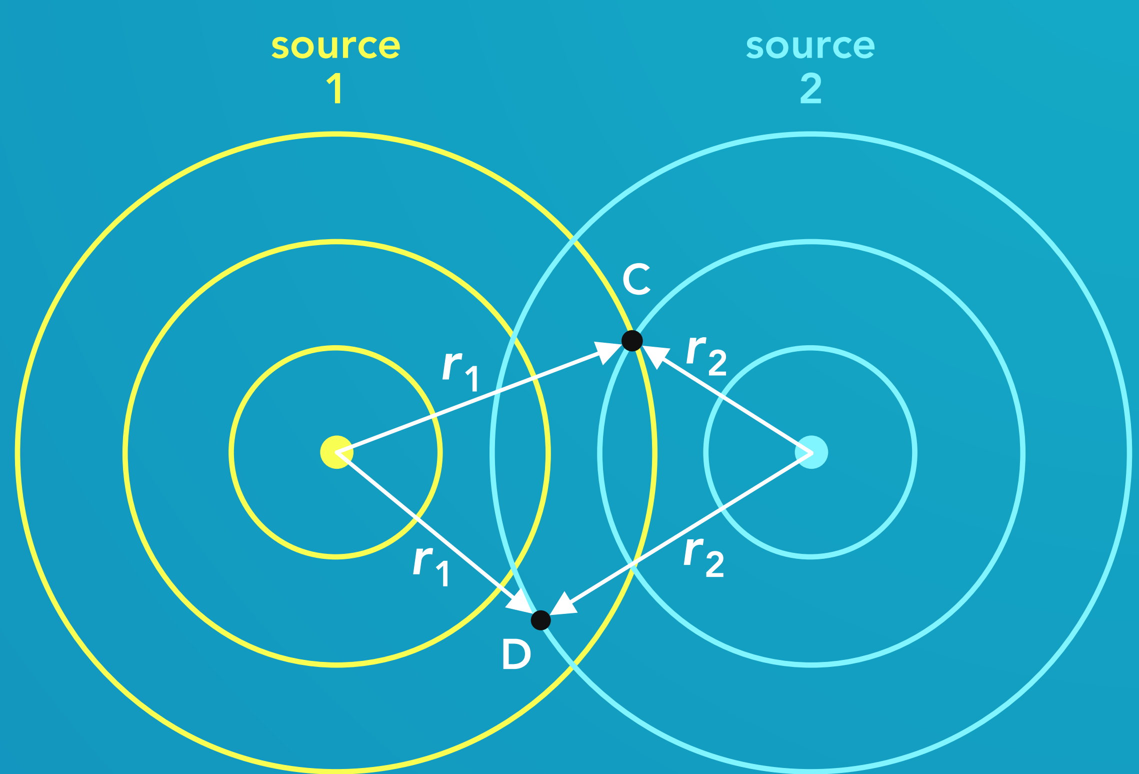
Constructive interference



$$\Delta d = \left(m + \frac{1}{2}\right)\lambda \quad m = 0, 1, 2, \ldots$$

Destructive interference

Radial (spherical) sound wave interference



$$\Delta r = |r_1 - r_2|$$

$$\Delta r = m\lambda \quad m = 0, 1, 2, \ldots$$

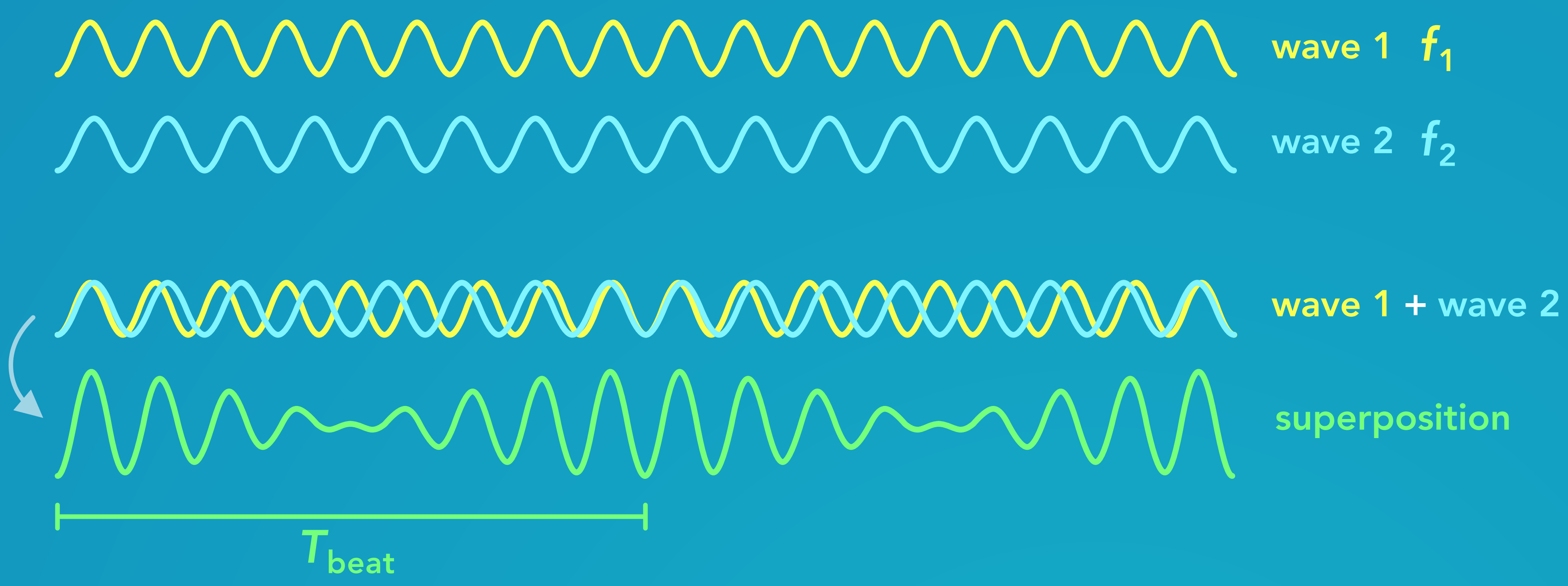
Constructive interference (point C)

$$\Delta r = \left(m + \frac{1}{2}\right)\lambda \quad m = 0, 1, 2, \ldots$$

Destructive interference (point D)

- When two sound waves with different frequencies interfere, the combined sound wave (the superposition of the two waves) will alternate between constructive and destructive interference.
- The frequency of this oscillation between high amplitude and zero amplitude is called the **beat frequency**.
- A listener will hear the sounds of wave 1 and wave 2 at the same time but the amplitude (volume or intensity) of the sound will oscillate at the beat frequency.

Variables		SI Unit
f	frequency	Hz



Beat frequency

$$f_{beat} = |f_1 - f_2|$$