# Sound

"Each celestial body, in fact each and every atom, produces a particular sound on account of its movement, its rhythm or vibration. All these sounds and vibrations form a universal harmony in which each element, while having it's own function and character, contributes to the whole."

Pythagoras (569-475 BC)

# Origin of Sound

* Produced by vibrations
  * Those vibrations compress and decompress the air (or other medium) around the vibrating object
  * The compressed areas are areas of higher pressure
    * *Compressions*
  * Decompressed areas have lower pressure
    * *Rarefactions*
* The frequency of the vibrating source almost always equals the frequency of the sound waves

# Frequency of Sound

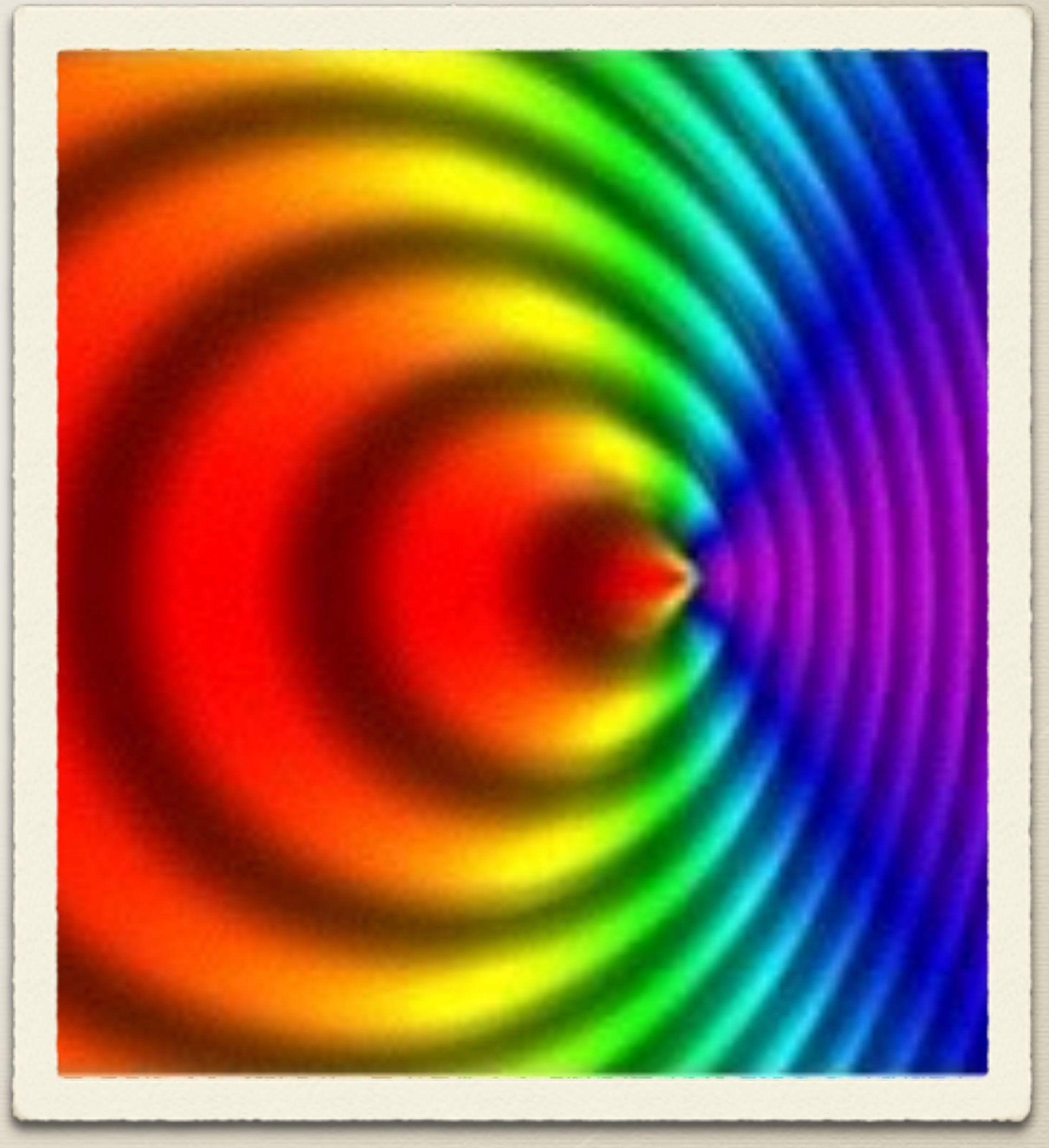
- *Pitch* is our brain's interpretation of frequency
  - High frequency → high pitch
  - Low frequency → low pitch
- Average young person can hear pitches from around 20 to 20, 000 Hz
- Sound frequencies below 20 Hz are called *infrasonic*
- Sound frequencies above 20,000 Hz are called *ultrasonic*

# The Doppler Effect

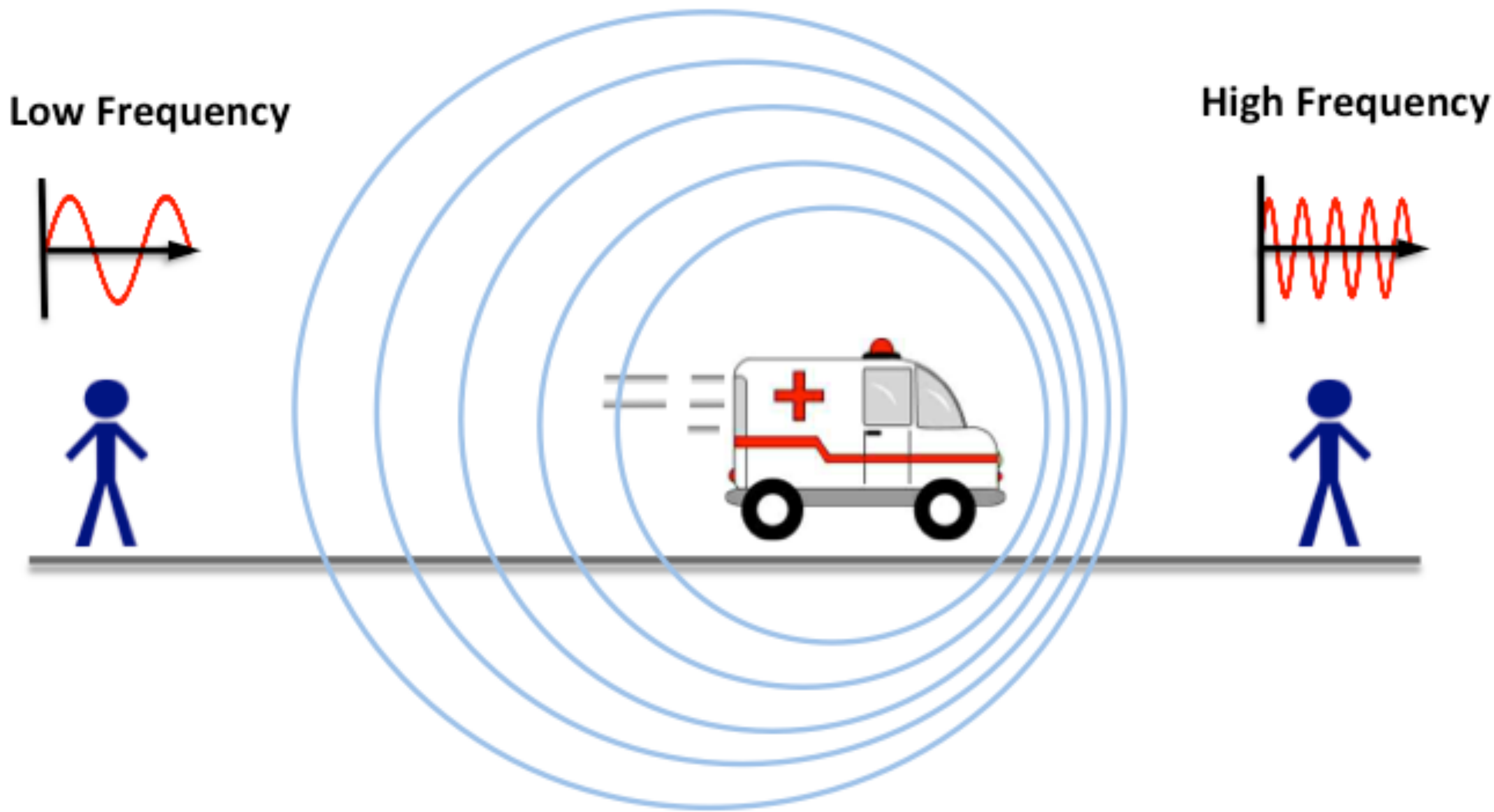
https://www.youtube.com/watch?v=h4OnBYrbCjY

# The Doppler Effect

* The Doppler Effect is the apparent change in *frequency* due to the motion of the source (or receiver)
    * The pitch sounds higher when the source is moving toward you
    * and lower when it's moving away

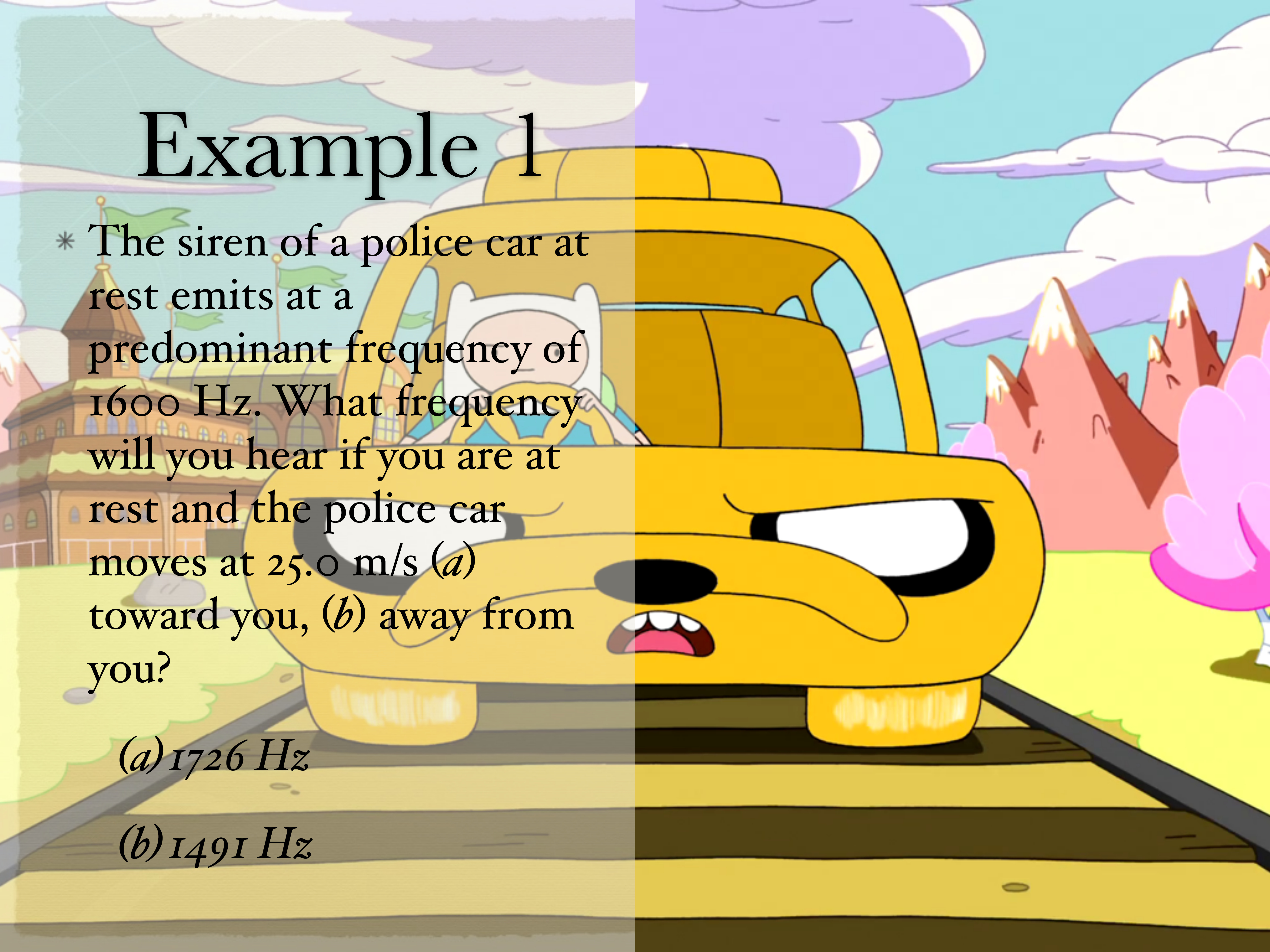


# Doppler Effect



# The Doppler Effect

- $f' = f/(1 \pm v_s/v)$
    - $f'$ = apparent frequency
    - $f$ = emitted frequency (according to the source)
    - $v_s$ = speed of source
    - $v$ = speed of sound
    - (-) source moving *toward* observer
    - (+) source moving *away* from observer



# Example 1

- The siren of a police car at rest emits at a predominant frequency of 1600 Hz. What frequency will you hear if you are at rest and the police car moves at 25.0 m/s (*a*) toward you, (*b*) away from you?

  *(a) 1726 Hz*

  *(b) 1491 Hz*

# Sanity Check

- When a source moves toward you, do you measure an increase or decrease in wave speed?
    - Neither! It is the *frequency* of a wave that undergoes a change where there is motion of the source, not the *wave speed*

# Loudness

* Loudness is the brain's interpretation of sound *intensity*
    * Intensity = power/area
    * $I \propto A^2$
* $\beta = 10 \log(I_1/I_0)$
    * $I_0 = 10^{-12}$ W/m²
    * Threshold of hearing
* Measure intensity in decibels (dB)

# Example 2

- The audience at the circus roars with applause at the acrobat's daring feats. The sound of the applause rings in at 68 dB. What is the intensity of the sound produced?

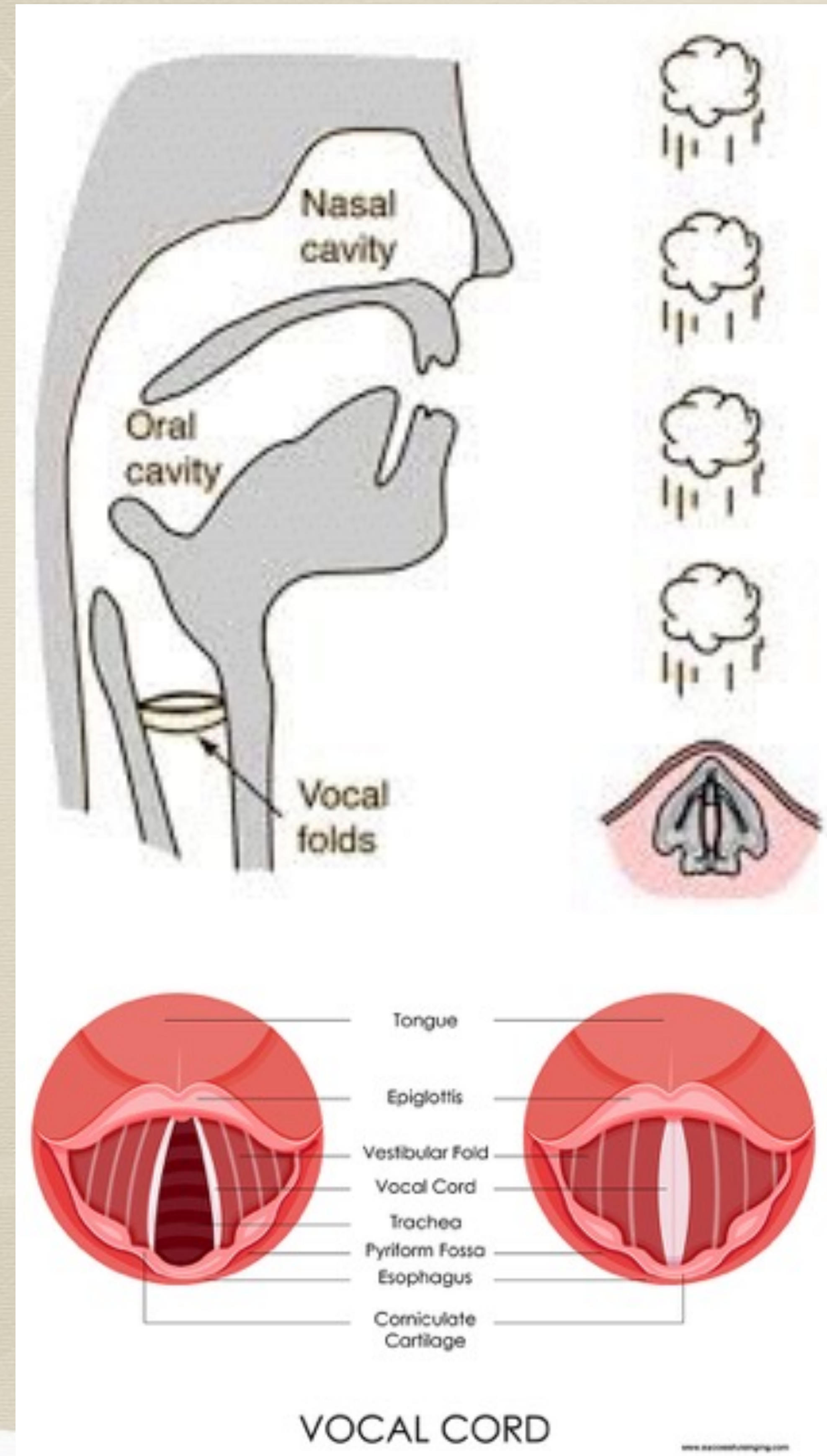
    - *Ans.* $I = 6.3 \times 10^{-6}\ W/m^2$

| Source of Sound | Decibel Level (dB) |
| --- | --- |
| Jet engine, at 30 m | 140 |
| Threshold of pain | 120 |
| Loud rock music | 115 |
| Old subway train | 100 |
| Average factory | 90 |
| Busy street traffic | 70 |
| Normal speech | 60 |
| Library | 40 |
| Close whisper | 20 |
| Normal Breathing | 10 |
| Hearing threshold | 0 |

# Loudness

* Intensity is logarithmic
  * For each increase in 10 dB, the intensity increases by a factor of 10
  * i.e. 10 dB is 10 times as intense as 0 dB and a tenth as intense as 20 dB
* Roughly speaking, the sensation of loudness follows the decibel scale
  * Thus, we say human hearing is approximately logarithmic

# Transmission of Sound Waves

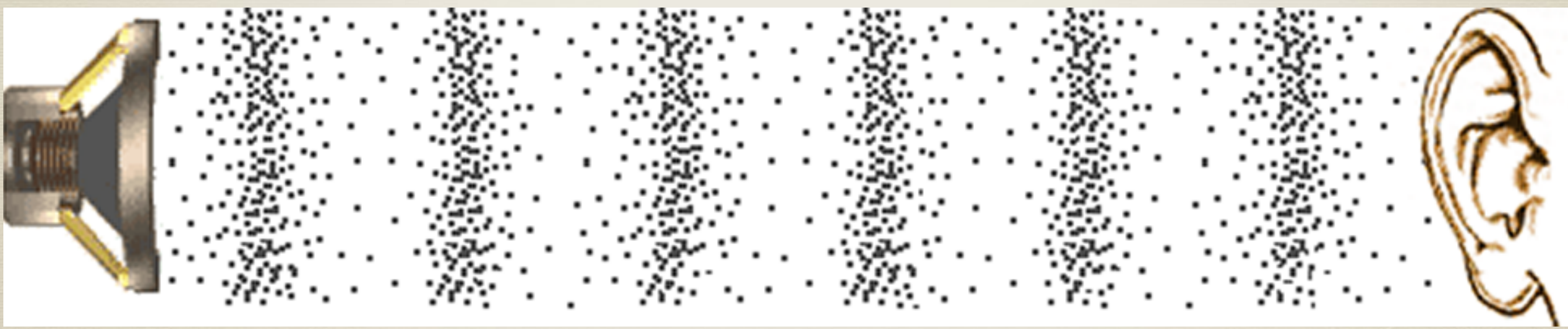



1. Vibration of the source

# Transmission of Sound Waves

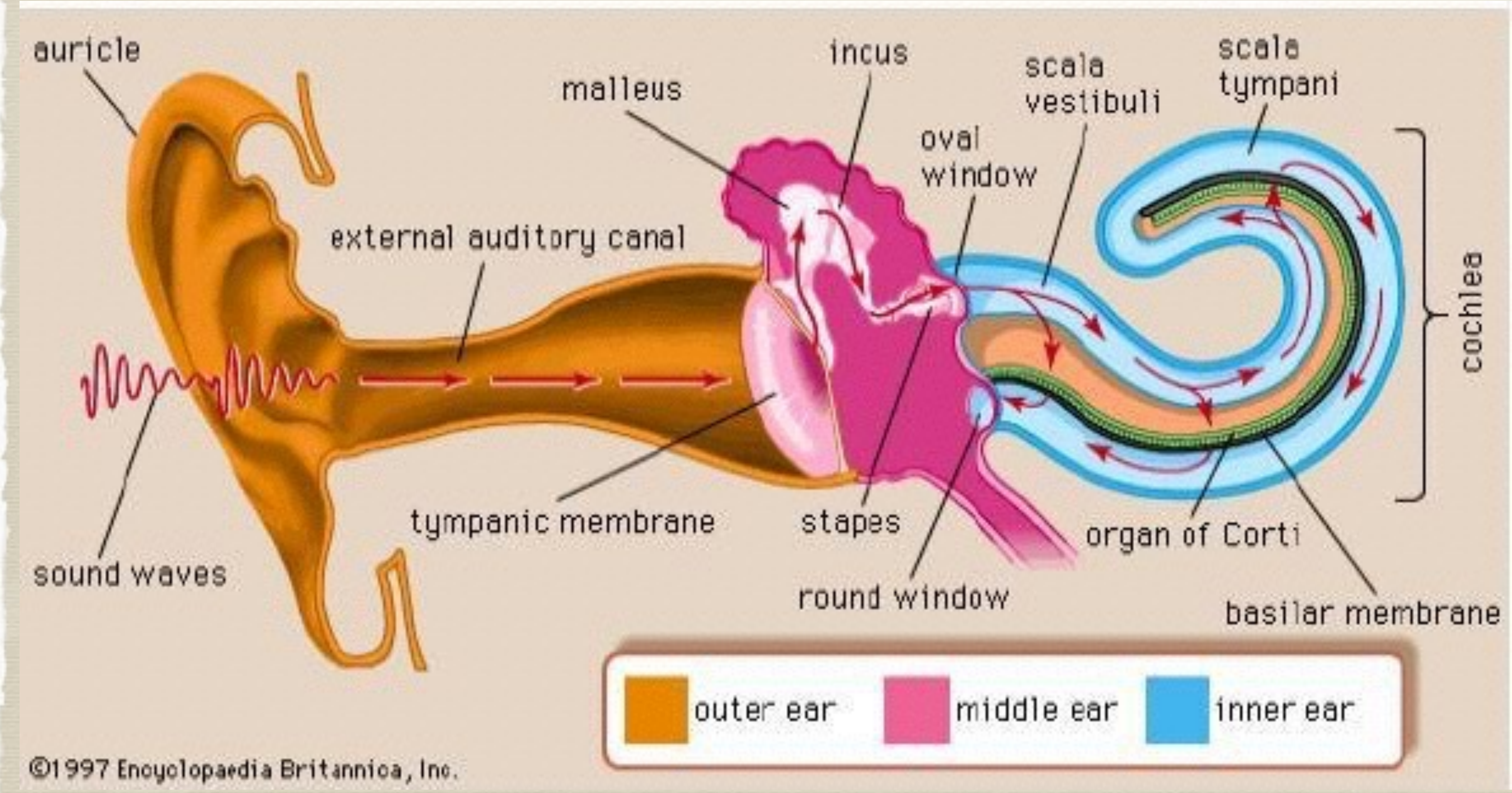
1. Vibration of the source

2. Compression waves thru the media



# Transmission of Sound Waves

1. Vibration of the source
2. Compression waves thru the media
3. Vibration of our eardrums



# Transmission of Sound Waves

1. Vibration of the source
2. Compression waves thru the media
3. Vibration of our eardrums
4. Electrical pulses to the brain

# Transmission of Sound Waves

* Sound needs a medium through which to travel
    * CANNOT travel through a vacuum
* The speed of sound is dependent on the *elasticity* of the medium
    * Elasticity is a measure of a material's propensity to retain its shape
    * Elasticity of: solids > liquids > gasses
    * Speed of sound: solids > liquids > gasses

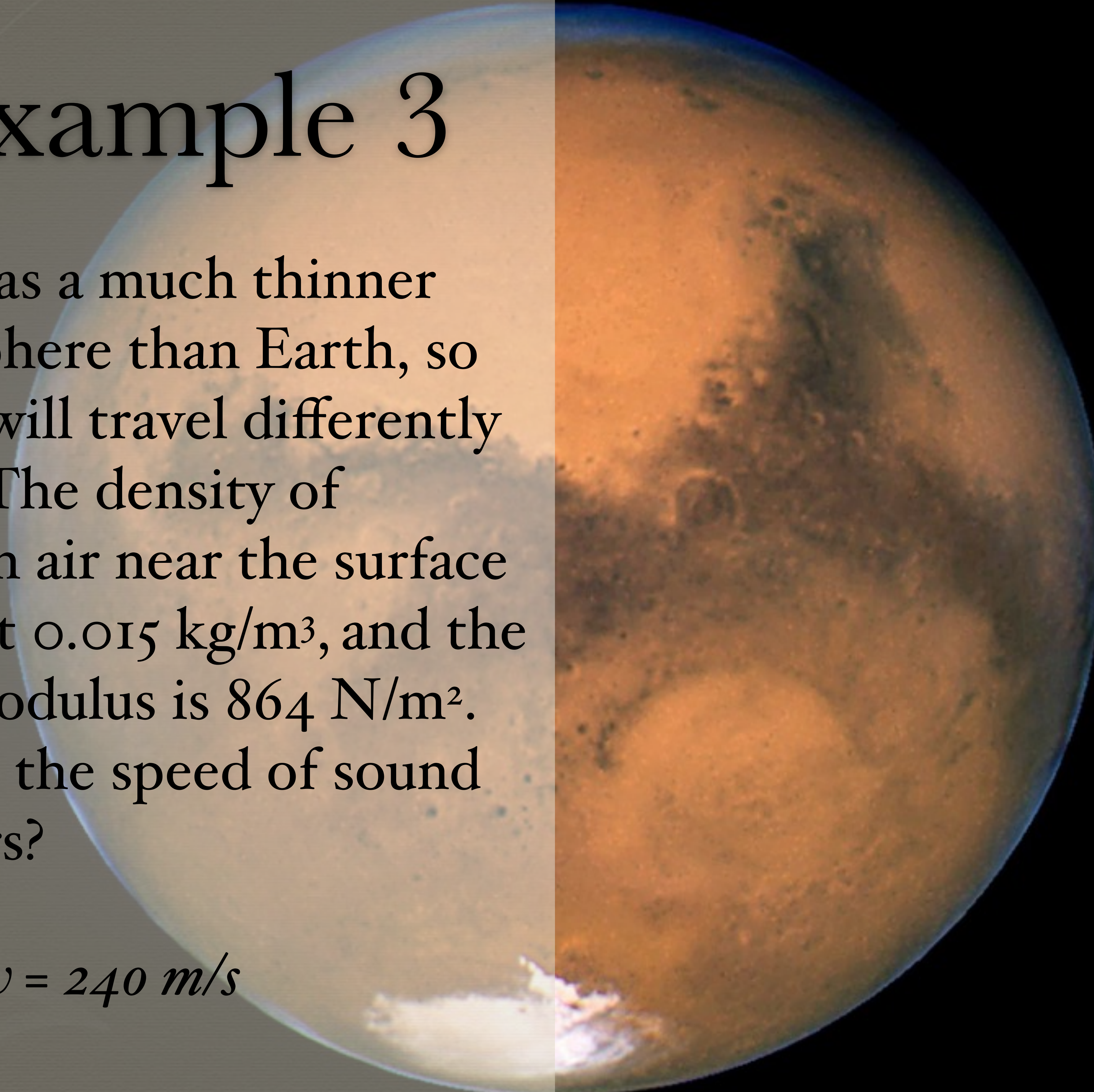
# Speed of Sound

* $v = \sqrt{E/\rho}$ *or* $v = \sqrt{B/\rho}$
    * $E$ = elastic modulus (for solids) in $N/m^2$
    * $B$ = bulk modulus (for liquids and gasses) in $N/m^2$
    * $\rho$ = density in $kg/m^3$

# Example 3

* Mars has a much thinner atmosphere than Earth, so sound will travel differently there. The density of Martian air near the surface is about 0.015 $kg/m^3$, and the bulk modulus is 864 $N/m^2$. What's the speed of sound on Mars?

  * *Ans.* $v = 240\ m/s$



# Speed of Sound

* In air (dry; 20°C):
    * $v \approx 343$ m/s (767 mph)
* In water (fresh; 20°C):
    * $v \approx 1{,}482$ m/s (3,315 mph)
* In steel:
    * $v \approx 5{,}960$ m/s (13,330 mph)
* In addition to faster, also clearer and louder

# Example 4

- How far away is a storm if you note a 3 second delay between a lightning flash and the sound of thunder?
  - $d = vt = 343\ m/s \times 3\ s = 1{,}029\ m$ (0.64 miles)

# Speed of Sound

* Why does higher elasticity mean a faster sound wave?
* Answer: Energy!
  * Sound waves move through oscillations that push and pull the material
  * Materials with high elasticity have greater internal energy to retain their shape
  * When the wave pushes the material, the material pulls *itself* back
  * This leaves more energy for the wave to put towards its kinetic motion

# Measuring the Speed of Sound

* Get in a group of 4
* You have 10 minutes to come up with a proposal of how to measure the speed of sound
* You can only use the tools we have available in this room
* *Minimize error*
* *Note: the average human reaction time is ~0.22 seconds*

# The Science of Music

"Music is the movement of sound to reach the soul for the education of its virtue."

– Plato

# Forced Vibrations

* When vibrations in one medium cause, or *force*, vibrations in another medium
* Virtually unavoidable, but much more interesting when used in clever ways
  * Such as by utilizing the *natural frequency* of the vibrating medium

# Natural Frequency

* Frequency at which minimum energy is required to produce and sustain forced vibrations
* Depends on the elasticity and shape of the vibrating object

# Resonance

* When the frequency of a forced vibration on an object matches the object's natural frequency, a dramatic increase in amplitude occurs
    * This phenomenon is called *resonance*
* Only occurs in highly elastic materials
    * Need a strong enough restoring force to pull the material back to its starting position
    * And enough energy to keep the object vibrating
* Ex. Swing

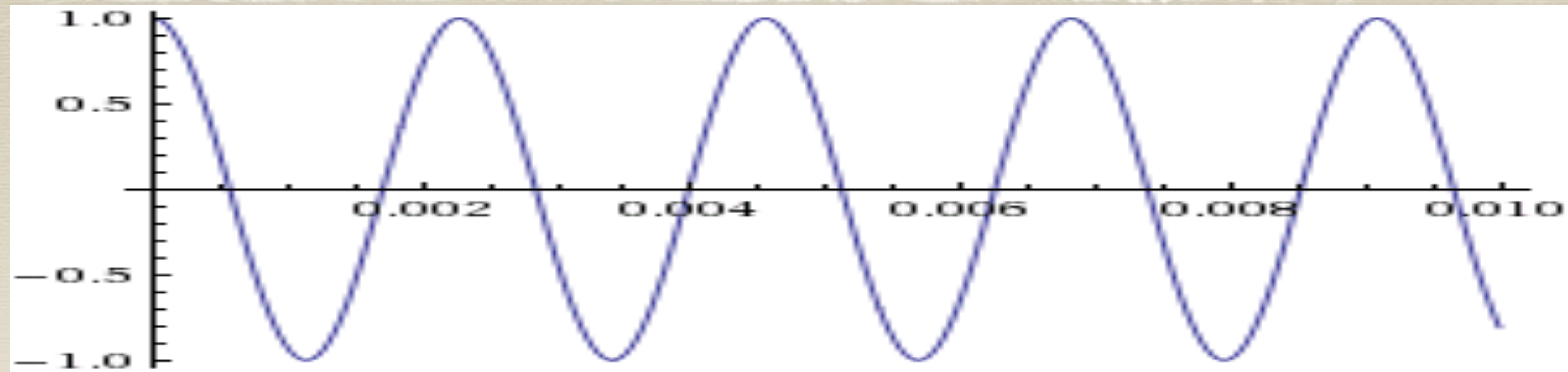
# Tacoma Narrows Bridge


https://www.youtube.com/watch?v=j-zczJXSxnw

# Interference

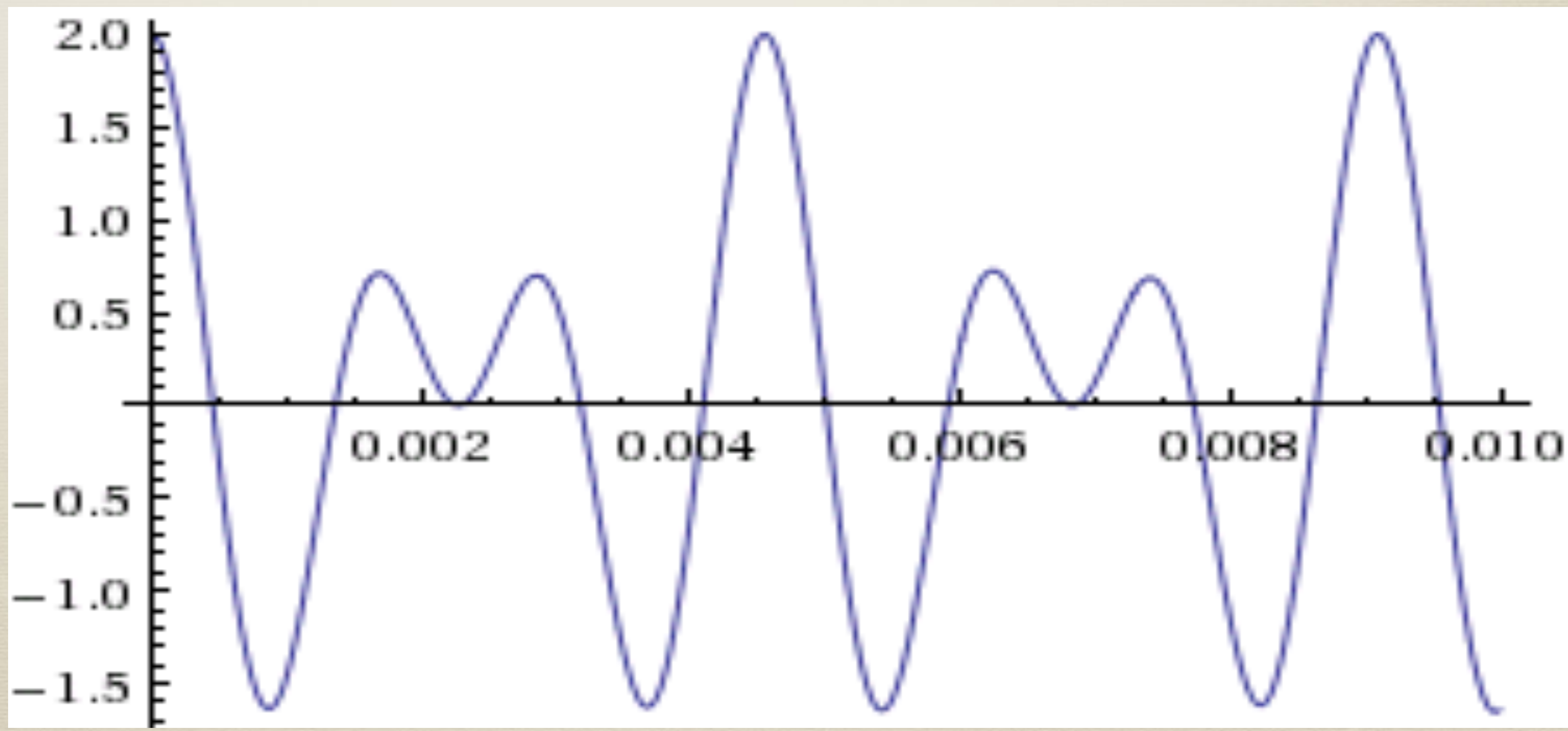
* Same rules for constructive and destructive interference apply
* What about interference between waves with different frequencies?

A: 440 Hz

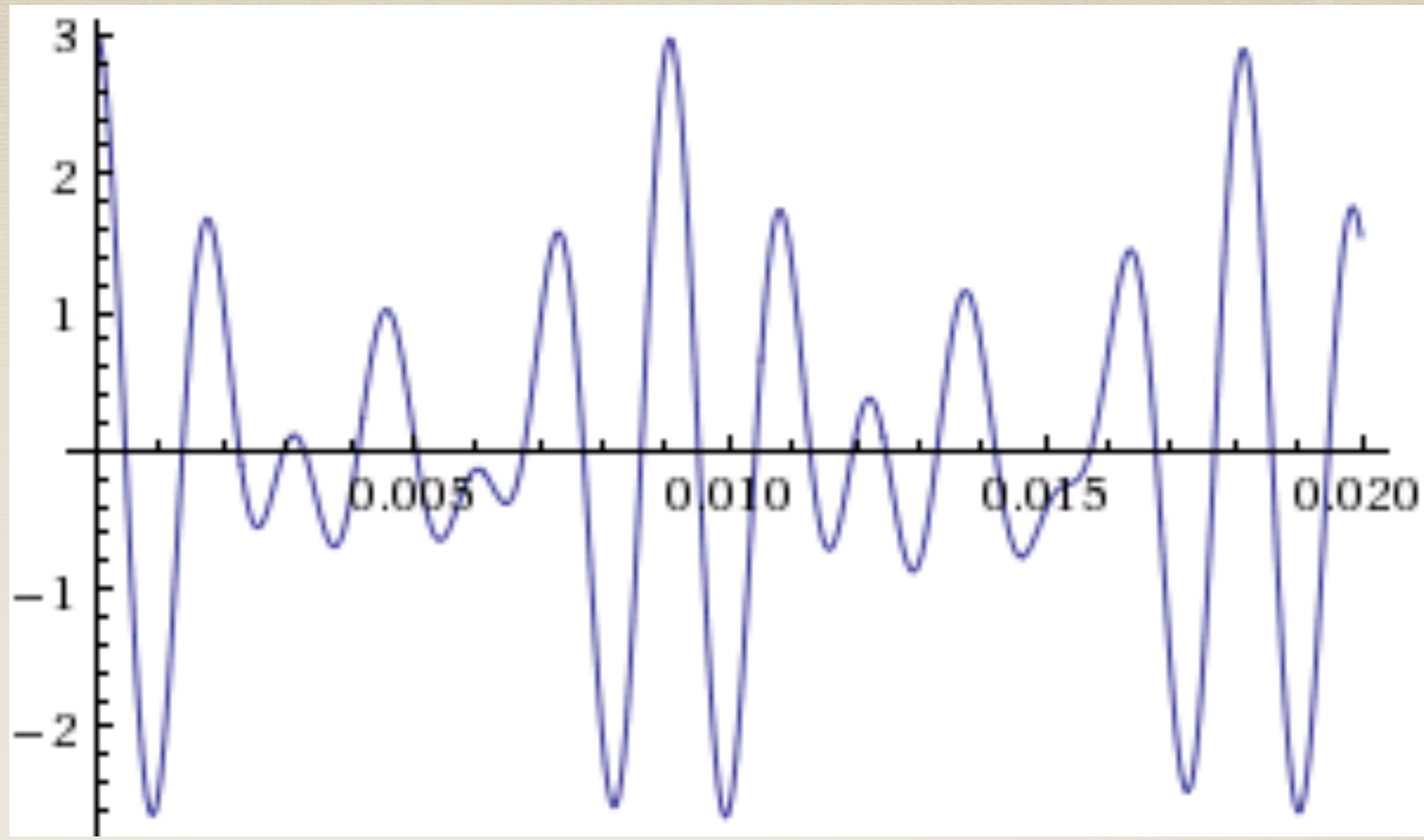



E: 660 Hz

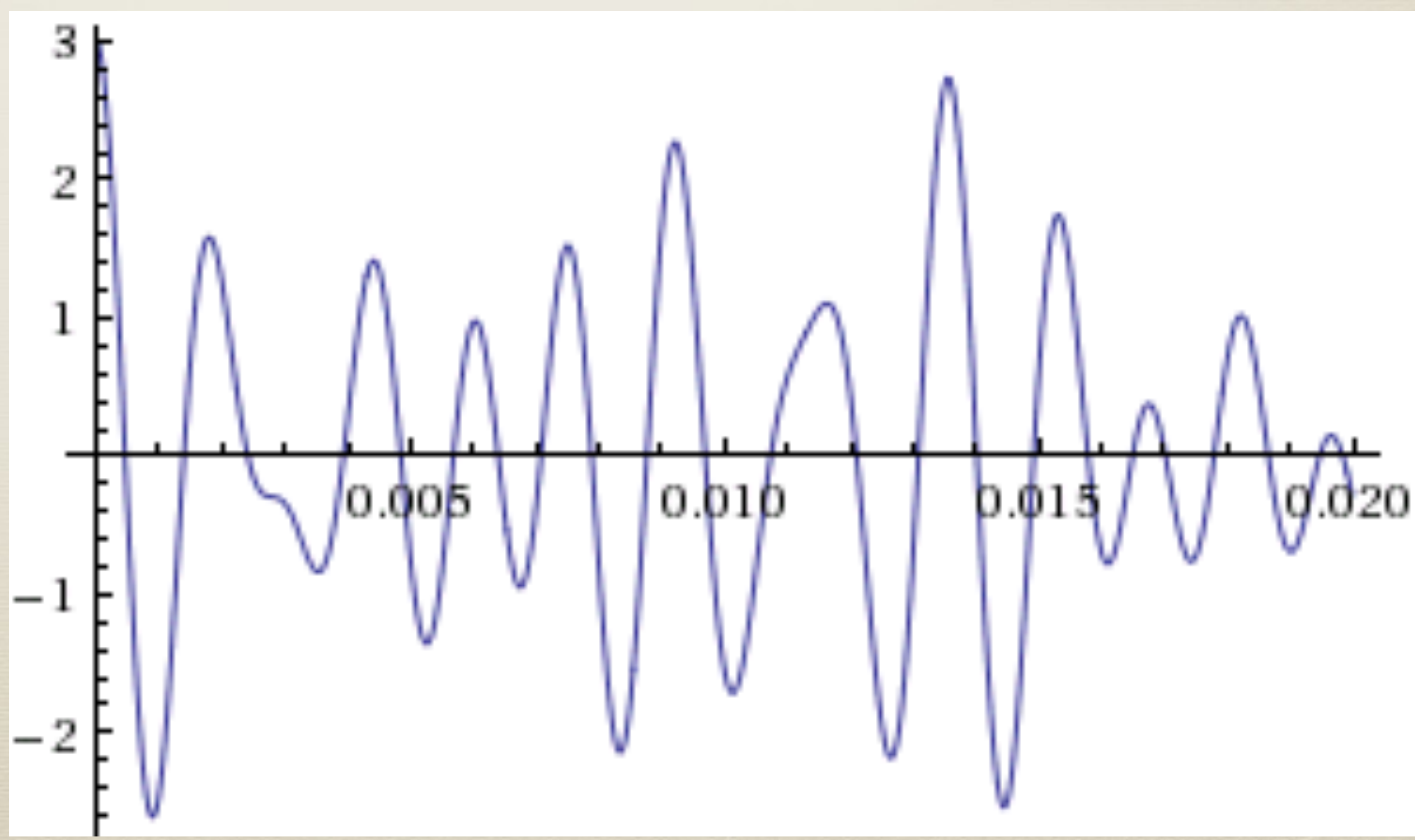

A + E



A Major

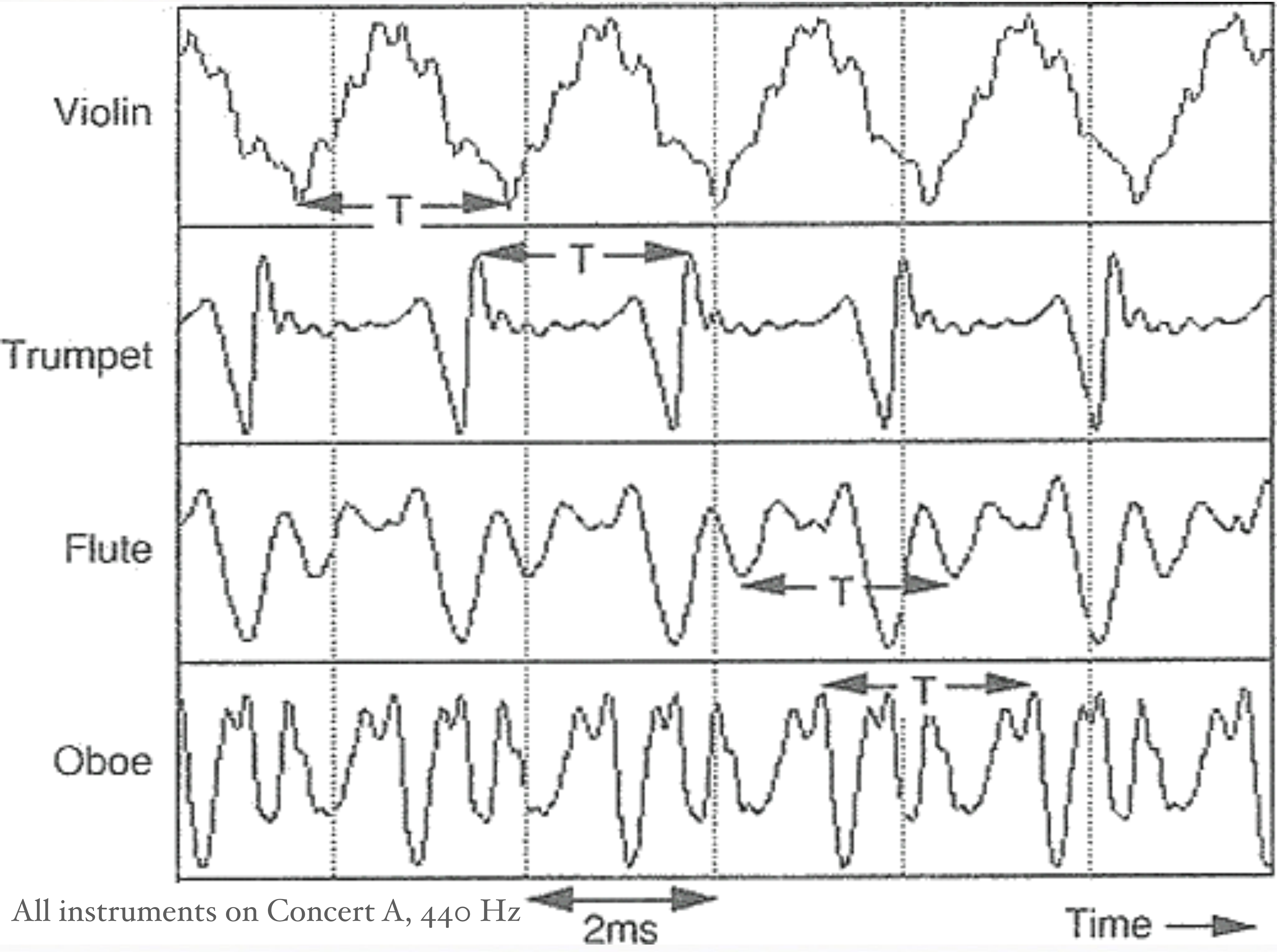



A Minor



# Timbre

* The character or quality of a musical sound or voice as distinct from its pitch and intensity
    * Also known as the tone quality or tone color
    * Bright vs Dark; Harsh vs Round
    * Biological interpretation of *wave form*
* http://public.wsu.edu/~jkrug/MUS364/audio/Waveforms.htm



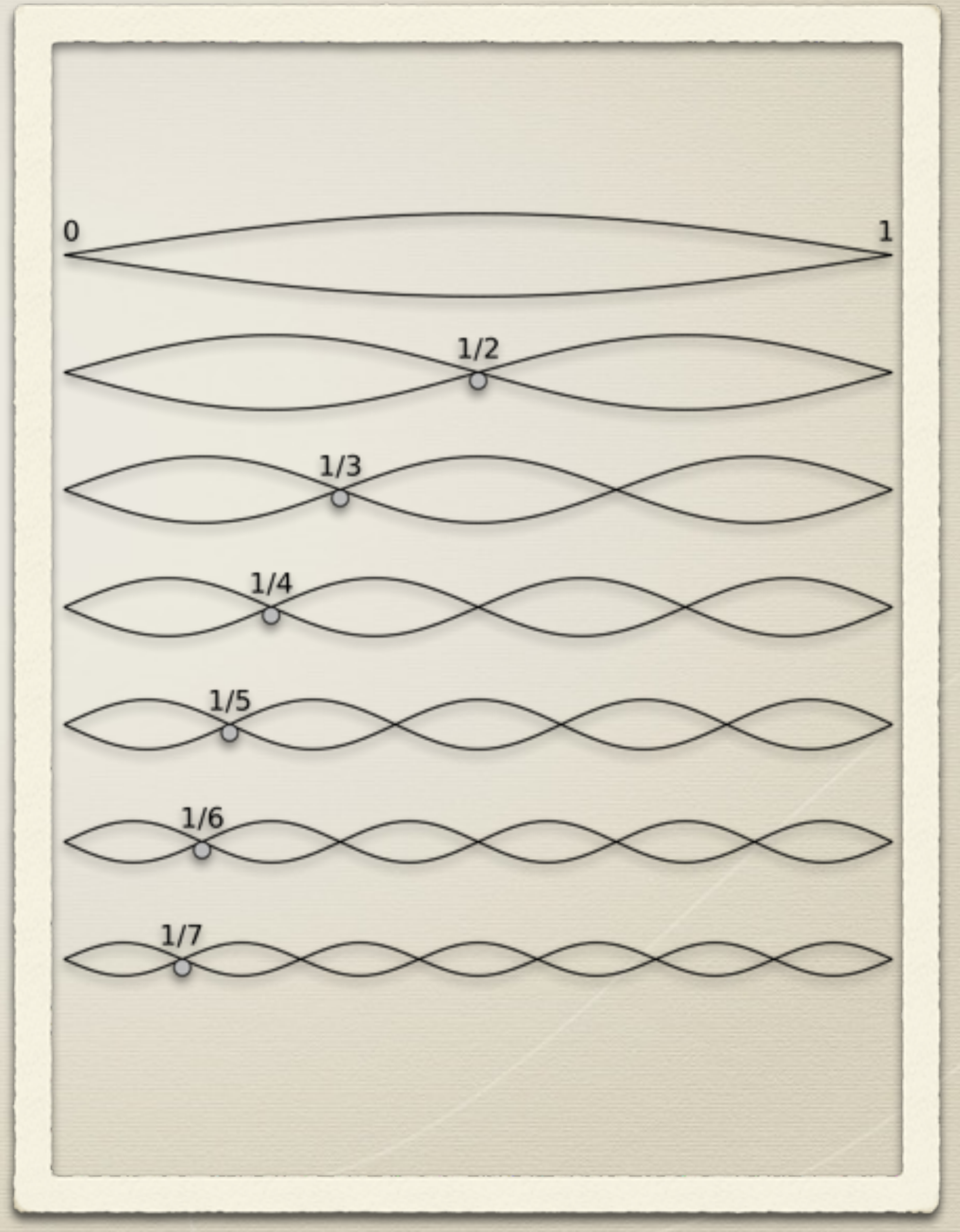
All instruments on Concert A, 440 Hz

# Harmonic Series

* The sequence off all multiples of a base frequency
  * E.g. base frequency, 1st harmonic: 110 Hz
  * 2nd harmonic: 220 Hz
  * 3rd harmonic: 330 Hz
* http://public.wsu.edu/~jkrug/MUS364/audio/Harmonics.htm

# Harmonic Series

- Pitched musical instruments are built to resonate at several frequencies simultaneously
- All you need are standing waves where the end points are nodes



# Question 1

* The highest key on a piano corresponds to a frequency about 150 times that of the lowest key. If the string for the highest note is 5.0 cm long, how long would the string for the lowest note have to be if it had the same mass per unit length and was under the same tension?

# Answer 1

- The velocity would be the same on each string, so the frequency is inversely proportional to the length $L$ of the string ($f = v/\lambda = v/2L$). Thus

- $L_L/L_H = f_H/f_L$

- $L_L = L_H(f_H/f_L) = (5.0 \text{ cm})(150) = 750 \text{ cm}$, or 7.5 m

# Question 2

* A 0.32-m-long violin string is tuned to play A above middle C at 440 Hz.

* What is the wavelength of the fundamental string vibration?

* What is the frequency and wavelength of the sound wave produced?

# Answer 2

- The wavelength of the fundamental is the wavelength of the standing wave on the string
  - $\lambda = 2L = 0.64$ m, or 64 cm
- The sound wave that travels outward in the air has the *same* frequency, 440 Hz. Its wavelength is
  - $\lambda = v/f = (343\ \text{m/s})/(440\ \text{Hz}) = 0.78$ m, or 78 cm
- Why is there a difference?

# Richter 15

- The biggest earthquake in recorded history happened in Chile in 1960. It measured 9.5 in the Richter scale.
- What if a magnitude 15 hit America? 20? 25?

# Richter Scale

- The Richter Scale has technically been replaced by the *moment magnitude* scale
- Richter Scale is a lot like the decibel system in that it's log-based and aims to scale the *energy* of the wave
- $M = \frac{2}{3}\log(E_1/E_0)$
  - $E_0 = 10^{4.4}$ J
  - Called the *standard earthquake*

# Richter Scale

- **A magnitude 9 earthquake already measurably alters the rotation of the Earth**
- **How much energy is released by a magnitude 15 earthquake?**
  - ***Ans. $7.9\times10^{26}$ J***
- **The most powerful bomb in the world is the *Tsar Bomba* hydrogen bomb**
- **A mag. 15 earthquake is about the same as 3.8 BILLION of those**


Illustration From October 2002 Issue of "Popular Mechanics" (pg. 69)

# Richter Scale

- How about magnitude 18.6?
  - *Ans.* $2.0\times10^{32}$ *J*
- That's the gravitational binding energy of the Earth
- So, the Death Star caused a magnitude 18.6 earthquake on Alderaan

# Richter Scale

- Your cell phone falling off your desk will hit the ground with about 1.2 J of energy.
- What magnitude earthquake will that create?
  - *Ans. M = -2.9*