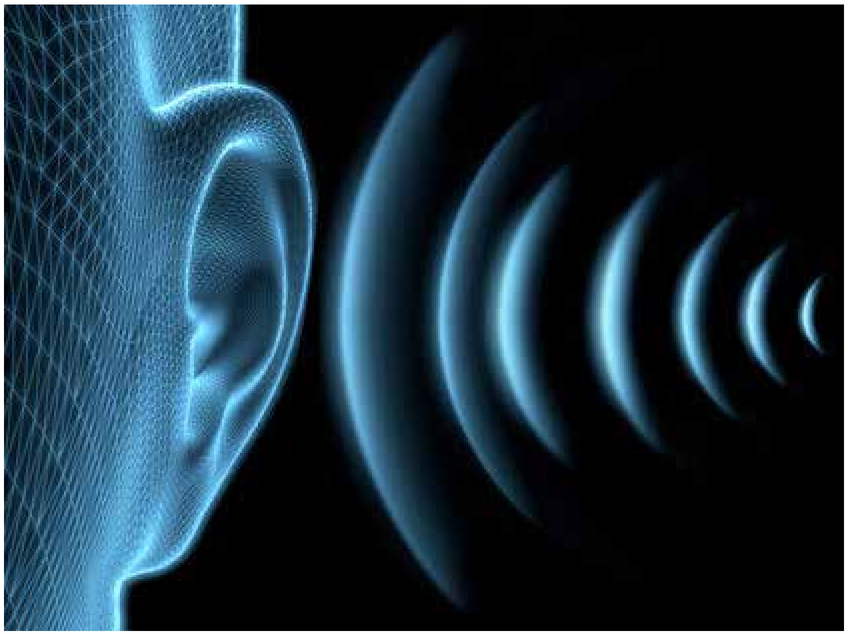
Waves and Oscillations

Lecture 13 – Sound Waves

Textbook sections 17.1 - 17.5



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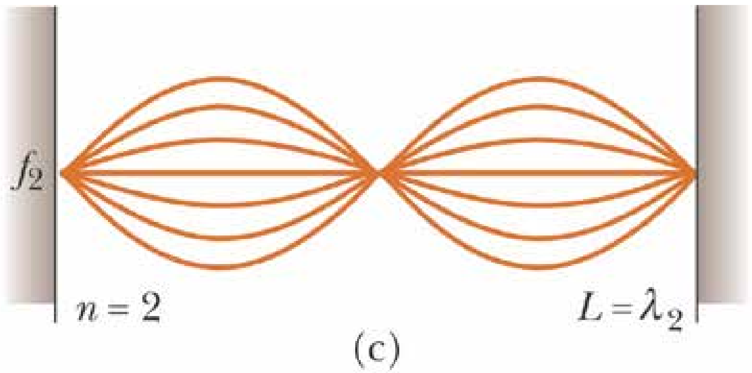
Last time: Standing Waves

Standing waves have the form:

$$y = 2A\sin(kx)\cos(\omega t)$$

- They can be split into a spatial and a temporal part.
- The particles that make up the medium undergo SHM with amplitude *2Asin(kx)*.

Last time: Standing Waves



Nodes: points on a standing wave with zero amplitude.

Antinodes: points on a standing wave at which maximum displacement occurs

"Natural frequencies"
Fundamental: n=1

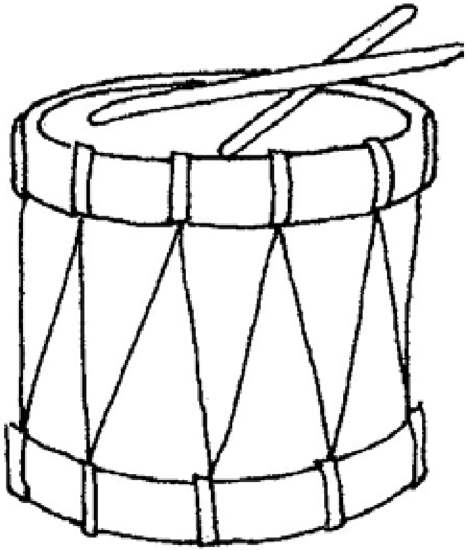
$$f_n = \frac{v}{\lambda_n} = n\frac{v}{2L} = \frac{n}{2L}\sqrt{\frac{T}{\mu}}$$

Sound waves

- Longitudinal waves
- Can move in three dimensions
- Need a medium/material to travel through
- As sound waves travel through air they move the molecules that make up the air, creating high and low pressure regions.
- Can be modelled as a sinusoidal wave (like on a string)

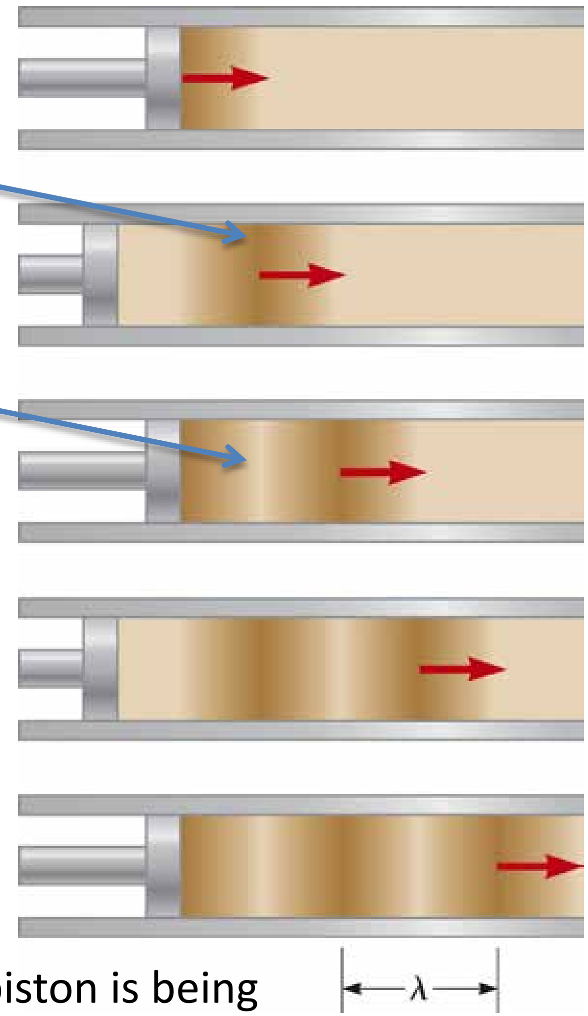
How to make a sound wave

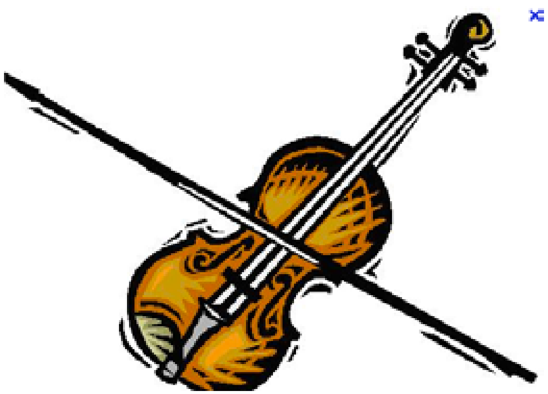
…and you thought we were done with pistons!



Compression
High Pressure

Rarefaction
Low Pressure



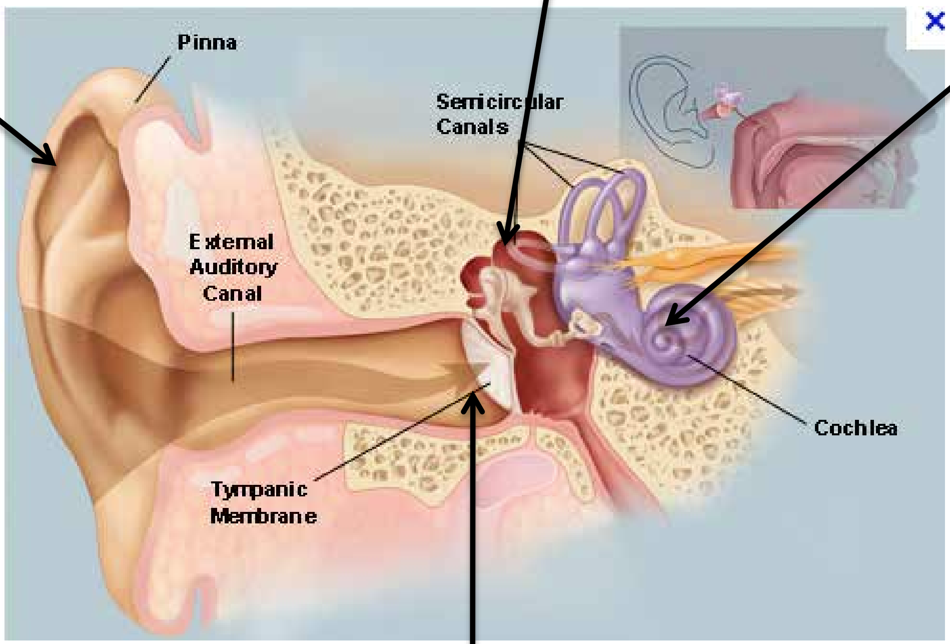


Assuming the piston is being moved with SHM

How we hear sound

Vibrations travel through these bones

Collects sound

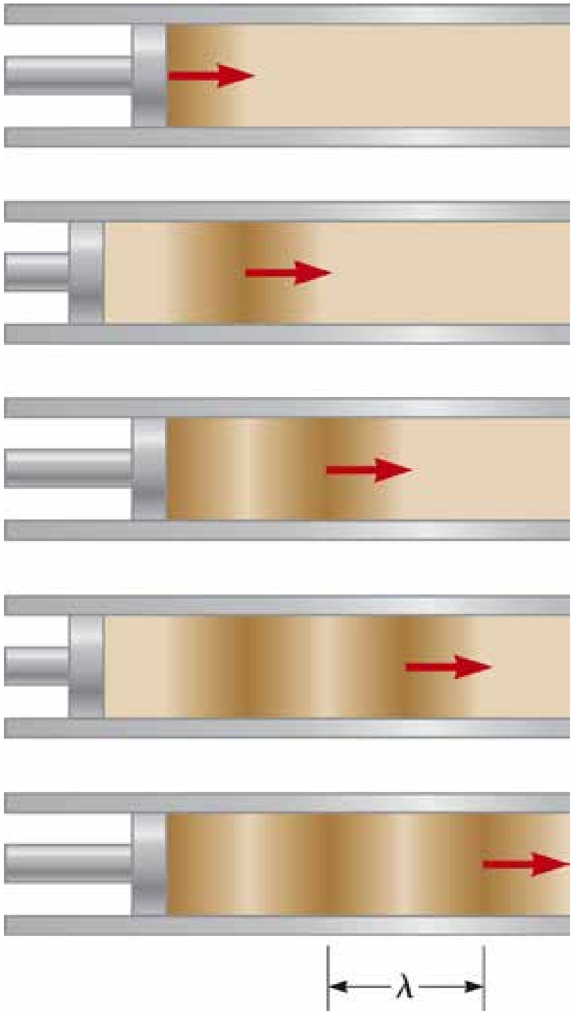


Cochlea: filled with fluid, hairs in it vibrate sending the signal to your brain.

Ear drum

Sound Waves:
Compression waves

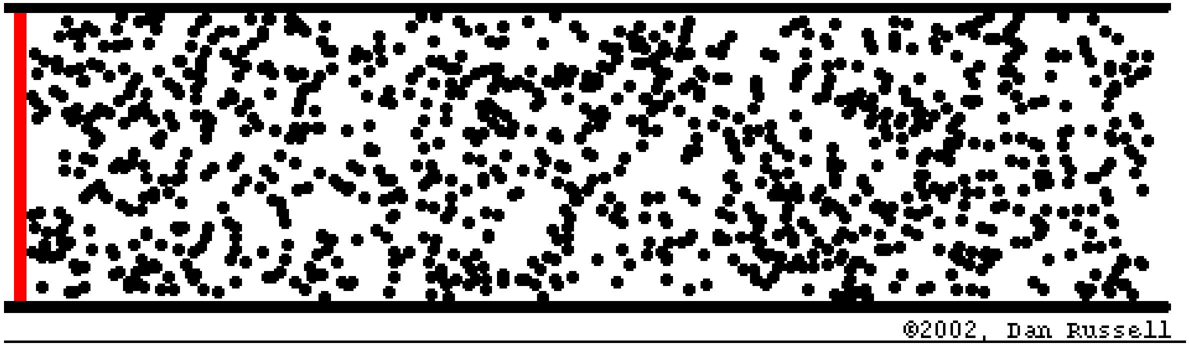
- Compressible gas, initially uniform density
- Piston suddenly moved to the right
  - Gas in front is compressed
- Piston comes to rest, but compression region continues to move
  - Corresponds to a longitudinal pulse travelling through the tube with speed v
  - Speed of the piston is <u>not</u> the same as the speed of the wave



Sound waves>How to make one...

- Move piston suddenly to **compress** the gas in front of it.

- Stop piston. But the compressed region continues to move → A longitudinal pulse travels through the tube with speed v (property of the medium).



- If piston moves in **SHM** with frequency f , we get a **travelling sinusoidal wave** with wavelength $\lambda = v/f$.

http://www.acs.psu.edu/drussell/demos.html

Now that we know how sound waves work…

Rubens Tube demo with more fire and good explanation

Sound waves>Quantitative...

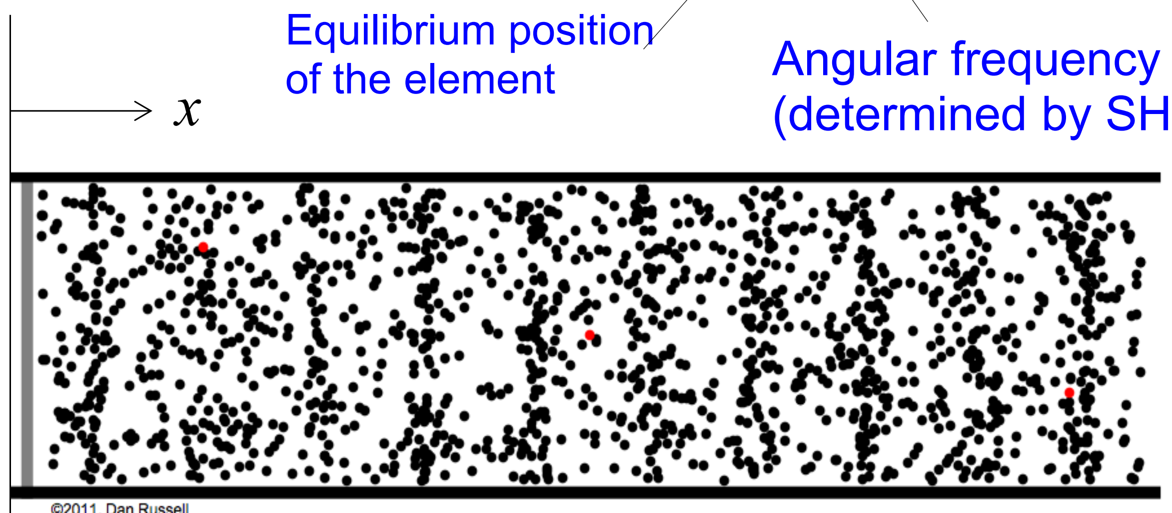
- Let $s(x, t)$ be the **displacement** of a small element of gas (red dots) from its equilibrium position .

–A travelling sinusoidal sound wave is described by

$$s(x,t) = s_{\mathrm{max}}\cos(kx - \omega t)$$

Equilibrium position of the element

Angular frequency (determined by SHM of piston)



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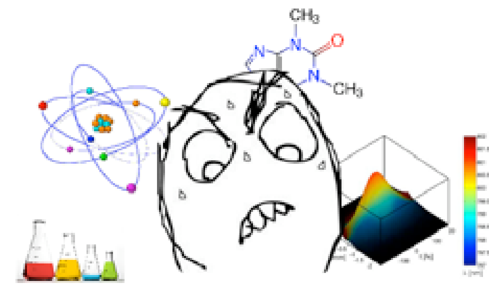
Quantitative


Do science

Let $s(x,t)$ be the position of a small element relative to its equilibrium position.

Each element moves with SHM parallel to direction of the wave.

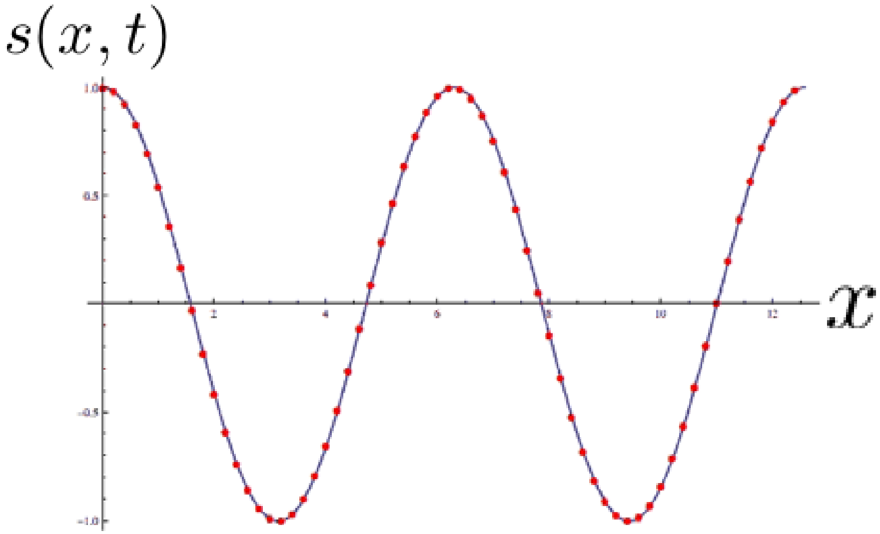
Displacement from equilibrium:

$$s(x,t) = s_{max} \cos(kx - \omega t)$$

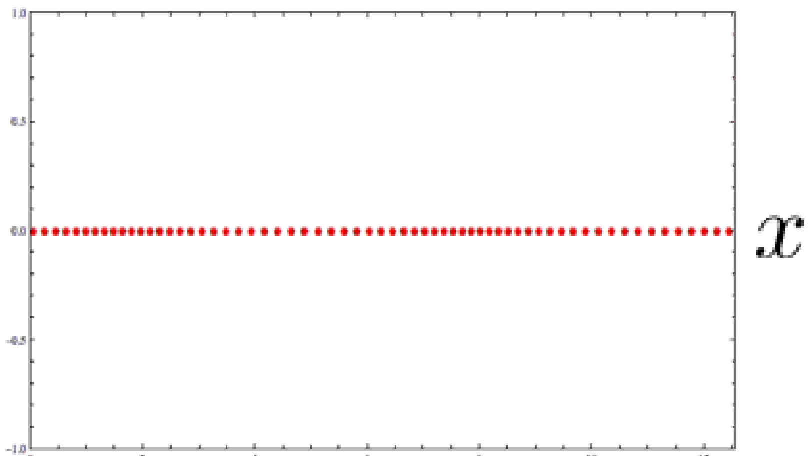
s_{max} is the displacement amplitude.

We can use this to derive an expression for the pressure, which is also periodic.

Pressure



$$s(x,t) = s_{max}\cos(kx - \omega t)$$



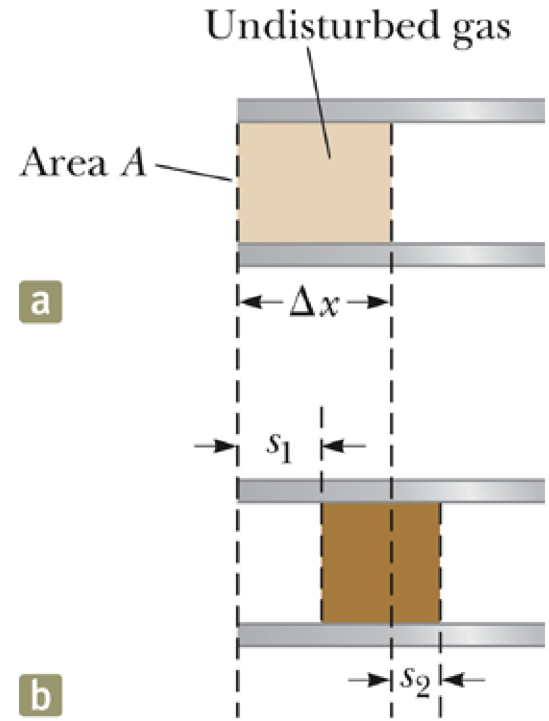
position of particles

Pressure

Consider a parcel of gas with thickness Dx

$$V_i = A\Delta x$$

BLACKBOARD



Stress is the force on a material.
Strain is what happens to the material under a given stress.
Under a tensile stress, at first, nothing might visibly happen to the material, but as stress increases, the material will bend (strain) and eventually break(strain)

If you blow across the top of an empty soft-drink bottle, a pulse of sound travels down through the air in the bottle. At the moment the pulse reaches the bottom of the bottle, what is the correct description of the displacement of elements of air from their equilibrium positions and the pressure of the air at this point?

1. The displacement and pressure are both at a maximum.
2. The displacement and pressure are both at a minimum.
3. The displacement is zero, and the pressure is a maximum.
4. The displacement is zero, and the pressure is a minimum.

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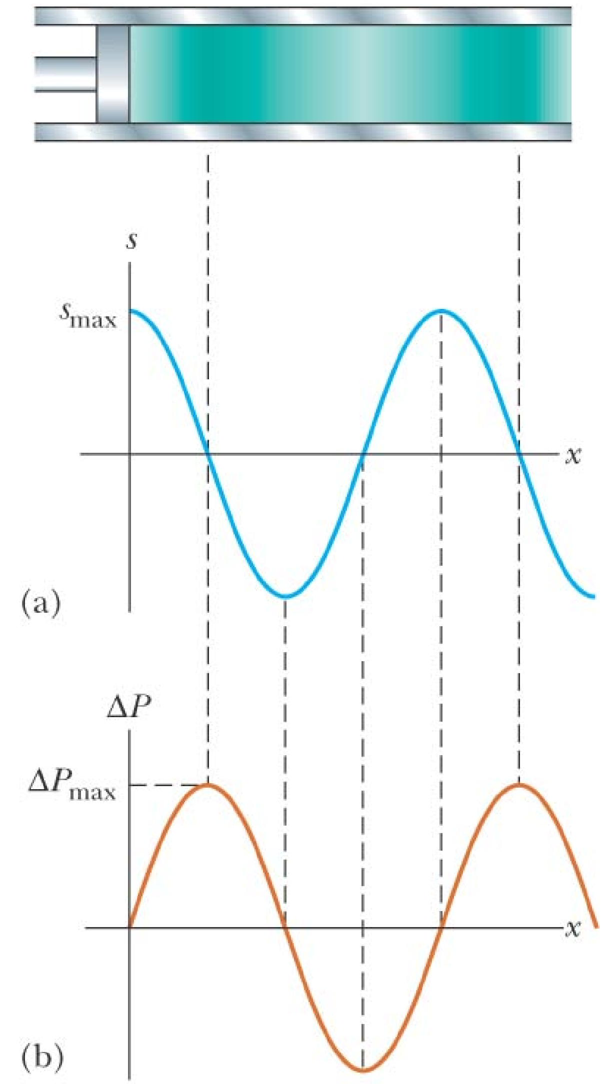
Periodic Sound Waves: Pressure *vs.* Displacement

- A sound wave may be considered either a displacement wave or a pressure wave
- Since $s\ (x, t) = s_{max} \cos\ (kx - wt)$ and $DP = Bs_{max}\ k \sin\ (kx - wt)$

  the pressure wave is 90^{o} ***out of phase*** with the displacement wave
  - The pressure is a maximum when the displacement is zero, etc.



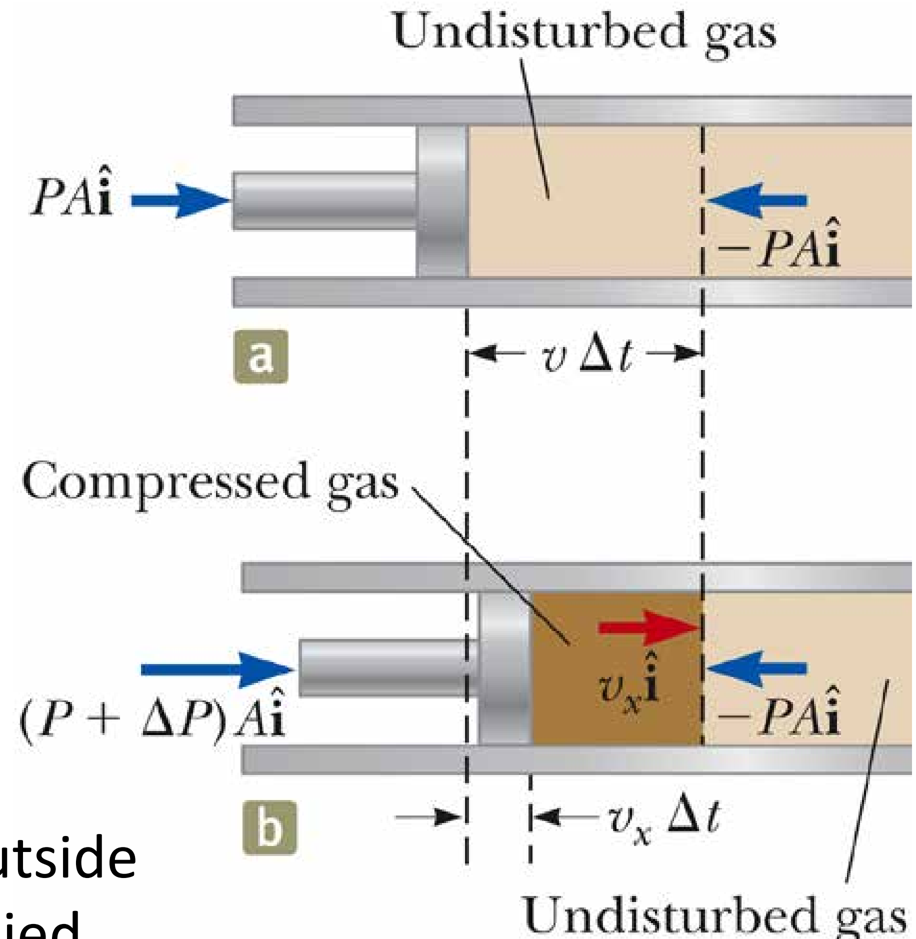
Let's take a short break

Pressure from sound waves

The speed of sound

Initial State

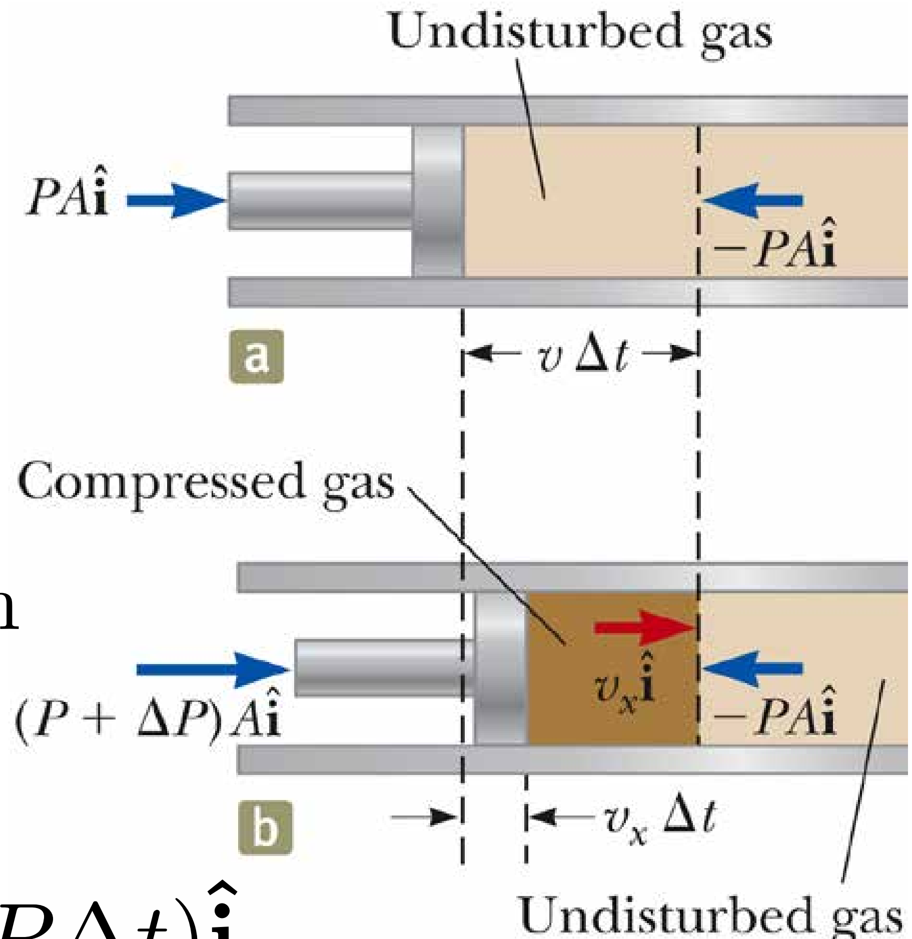
Final State



Force applied on piston from outside is in equilibrium with force applied by gas on the piston.

The speed of sound

After time interval Δt every bit of gas in the element is moving to the right with speed v_x . The speed of sound in this medium is v



$$\text{Impulse} = \Delta\text{momentum}$$

$$\mathbf{I} = \sum \mathbf{F}\Delta t = (A\Delta P\Delta t)\hat{\mathbf{i}}$$

Sum of forces, using definition of pressure P=F/A

The speed of sound (liquid or gas)

$$v = \sqrt{\frac{B}{\rho}}$$

$$v = \sqrt{\frac{\text{elastic property}}{\text{inertial property}}}$$

$$v = \sqrt{\frac{T}{\mu}} \text{ on a string}$$

Speed of Sound in Air

- The speed of sound also depends on the temperature of the medium
  - Particularly important with gases
- For air, the relationship between the speed and temperature is

$$v = (331 \text{ m/s})\sqrt{1 + \frac{T_C}{273^\circ \text{ C}}}$$

  - 331 m/s is the speed at 0^o C
  - T_C is the air temperature in Celsius

- Exercise for student: show that $v = (331 \text{ m/s})\sqrt{\frac{T_K}{273}}$ where T_K is temperature in Kelvin

The speed of sound

TABLE 17.1 *Speed of Sound in Various Media*

Medium	v (m/s)	Medium	v (m/s)	Medium	v (m/s)
Gases		**Liquids at 25°C**		**Solids**[a]	
Hydrogen (0°C)	1 286	Glycerol	1 904	Pyrex glass	5 640
Helium (0°C)	972	Seawater	1 533	Iron	5 950
Air (20°C)	343	Water	1 493	Aluminum	6 420
Air (0°C)	331	Mercury	1 450	Brass	4 700
Oxygen (0°C)	317	Kerosene	1 324	Copper	5 010
		Methyl alcohol	1 143	Gold	3 240
		Carbon tetrachloride	926	Lucite	2 680
				Lead	1 960
				Rubber	1 600

[a]Values given are for propagation of longitudinal waves in bulk media. Speeds for longitudinal waves in thin rods are smaller, and speeds of transverse waves in bulk are smaller yet.

Pressure and displacement

$$\Delta P_{max} = B s_{max} k = (\rho v^2) s_{max} (\frac{\omega}{v}) = \rho v \omega s_{max}$$

Pressure amplitude

More useful to relate the maximum change in pressure to **density** than to bulk modulus.

Question

A sound wave propagates in air at 27^{o} C with frequency 4.00 kHz. It passes through a region where the temperature gradually changes and then moves through air at 0^{o} C. Give numerical answers to the following questions to the extent possible and state your reasoning about what happens to the wave physically.

(a) What happens to the speed of the wave?

(b) What happens to the frequency?

(c) What happens to the wavelength?

Intensity of Periodic Sound Waves

Waves carry energy, sound waves also carry energy.

As a piston moves back and forward creating sound waves, it is doing work on a gas.

$$W = \mathbf{F} \cdot \mathbf{x}$$

The rate of work done gives us the power

$$\mathrm{Power} = \mathbf{F} \cdot \mathbf{v_x}$$

Intensity of Periodic Sound Waves

The average power is then given by:

$$(\text{Power})_{avg} = \frac{1}{2}\rho v \omega^2 A s_{max}^2$$

Intensity is the power per unit area:

$$I \equiv \frac{(\text{Power})_{avg}}{A}$$

Intensity of Periodic Sound Waves

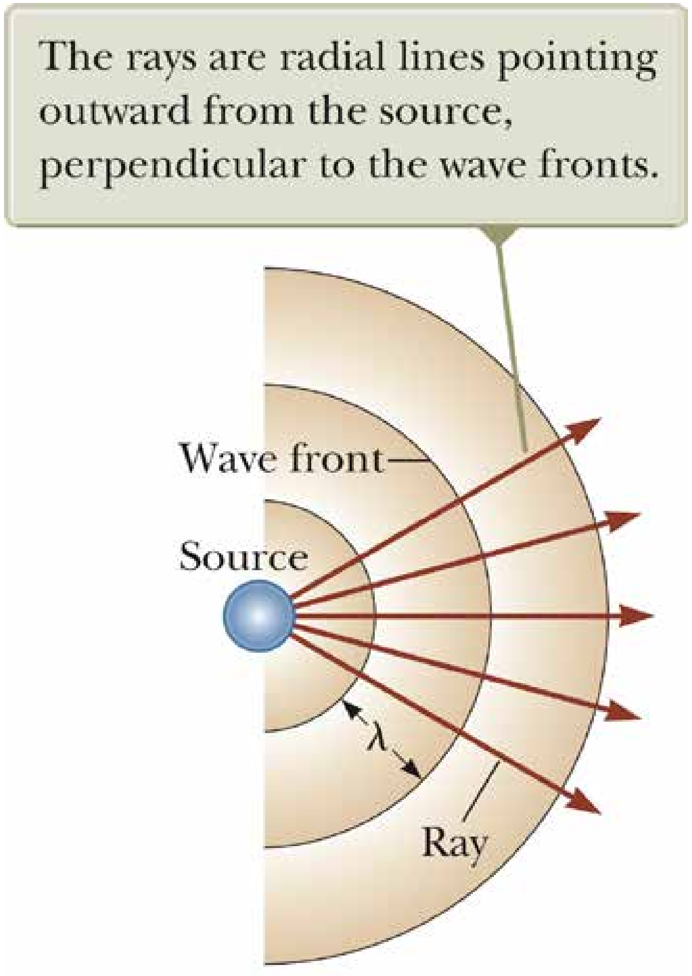
So for this case (the wave was moving in the x direction)

$$I = \frac{1}{2}\rho v(\omega s_{max})^2$$

Or in terms of pressure (remember $\Delta P_{max} = \rho v \omega s_{max}$)

$$I = \frac{(\Delta P_{max})^2}{2\rho v}$$

But sound waves can travel in 3 dimensions….



$$I = \frac{(\text{Power})_{avg}}{4\pi r^2}$$

This is an inverse-square law
(happens all the time in physics,
from the subatomic to galactic scale)

A vibrating guitar string makes very little sound if it is not mounted on the guitar body. Why does the sound have greater intensity if the string is attached to the guitar body?

1. The string vibrates with more energy.
2. The energy leaves the guitar at a greater rate.
3. The sound power is spread over a larger area at the listener’s position.
4. The sound power is concentrated over a smaller area at the listener’s position.
5. The speed of sound is higher in the material of the guitar body.
6. None of these answers is correct.

https://goo.gl/forms/fLt4qGqPGz99evEu1

QUESTION!!!!!

The faintest sounds the human ear can detect at a frequency of 1000 Hz correspond to an intensity of about 1.00×10^{-12} W/m^2, which is called the *threshold of hearing*. The loudest sound that the ear can tolerate at this frequency corresponds to an intensity of about 1.00 W/m^2, the *threshold of pain.* Determine the pressure amplitude and displacement amplitude associated with these two limits.

$r_{air} = 1.2$ kg/m^3

Sound speed $c_s = 343$ m/s