CHAPTER 16: TRAVELING WAVES

Lots of Simple Harmonic Oscillators moving together!

E.g., Stadium Wave

Lots of Simple Harmonic Oscillators moving together!

Q: What is a wave?
A: An organized disturbance that travels at a well defined speed.
e.g.,
Sound waves in air: 300 m/s
Light waves: 3×10^8 m/s

Note: Medium (if there's one) may oscillate, but it doesn't move w/ the wave, or have bulk motion.

Types of Waves

We will consider three general types of waves:

1.) **Mechanical Waves**

- Require a medium to propagate
- The wave speed is determined by the elastic properties and inertia of the medium
- Can be transverse or longitudinal to the wave direction (see next slide)
- Video of mechanical waves *(be honest, is this video too boring?)*
- Examples: wave on a string, sound waves, water waves (me playing on a wave last summer), stadium wave(?).

2.) **Electromagnetic Waves**

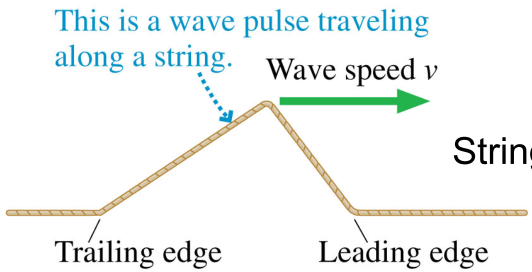
- Requires no medium to propagate (. . . *Interesting…what's waving then?*)
- Disturbances in the electromagnetic fields that travel in vacuum at the speed of light. $(c = 3 \times 10^8\ m/s)$
- e.g. visible light, radio waves, x-rays, etc.

3.) **Matter Waves**

- Microscopic particles, like electrons, have observable wave properties.
- This is Quantum Mechanics
- What's doing the waving?

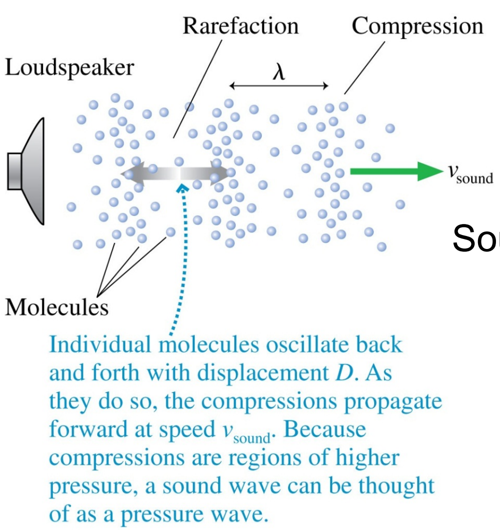
TYPES OF WAVES

Mechanical Wave



String

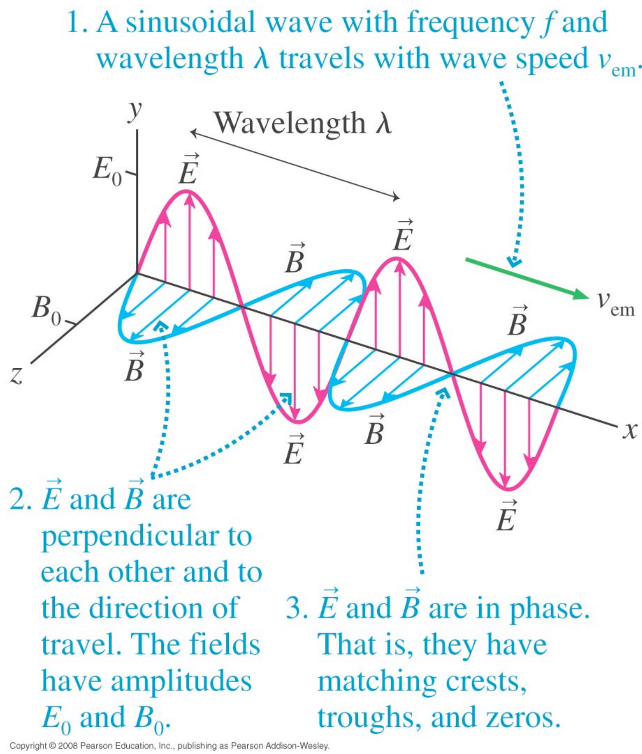
Water



Sound

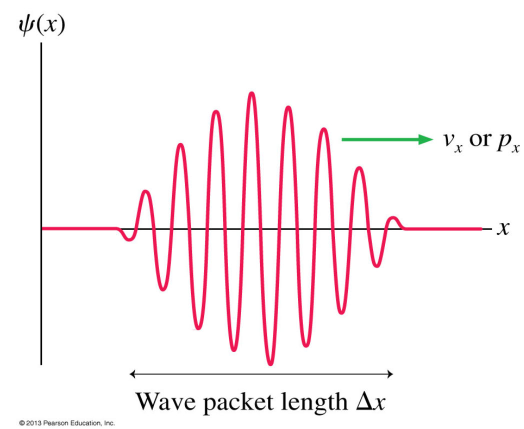
Electromagnetic Wave

Light



Probability Wave

Photon, Electron, even atom



All examples shown here are transverse waves, except sound which is longitudinal.

Polarization of Wave: The wave is said to be *polarized* along the direction of motion of the oscillators. This leads to two basic types of waves:

Transverse and Longitudinal Waves:

LET'S WATCH A VIDEO

In **transverse waves**, the oscillators displace about their equilibrium positions in a direction *perpendicular* to the direction of propagation of the wave.
Examples: water waves, light waves

In **longitudinal waves**, the oscillators displace about their equilibrium positions *along* the direction of propagation of the wave.
Examples: sound waves

Earthquake waves have both transverse and longitudinal components.

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E.g., Stadium Wave

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e.g.,

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Light waves: 3×10^8 m/s

Note: Medium (if there's one) may oscillate, but it doesn't move w/ the wave, or have bulk motion.

Let's watch a video…

"Medium" through which wave moves? ____________

Note: Wave speed is NOT equal to individual oscillator speed!

Q: What does the wave speed depend on?

A: __________________ and __________________

KEY POINT 1: What's the wave speed? (Sec. 16.1)

E.g., Stadium Wave

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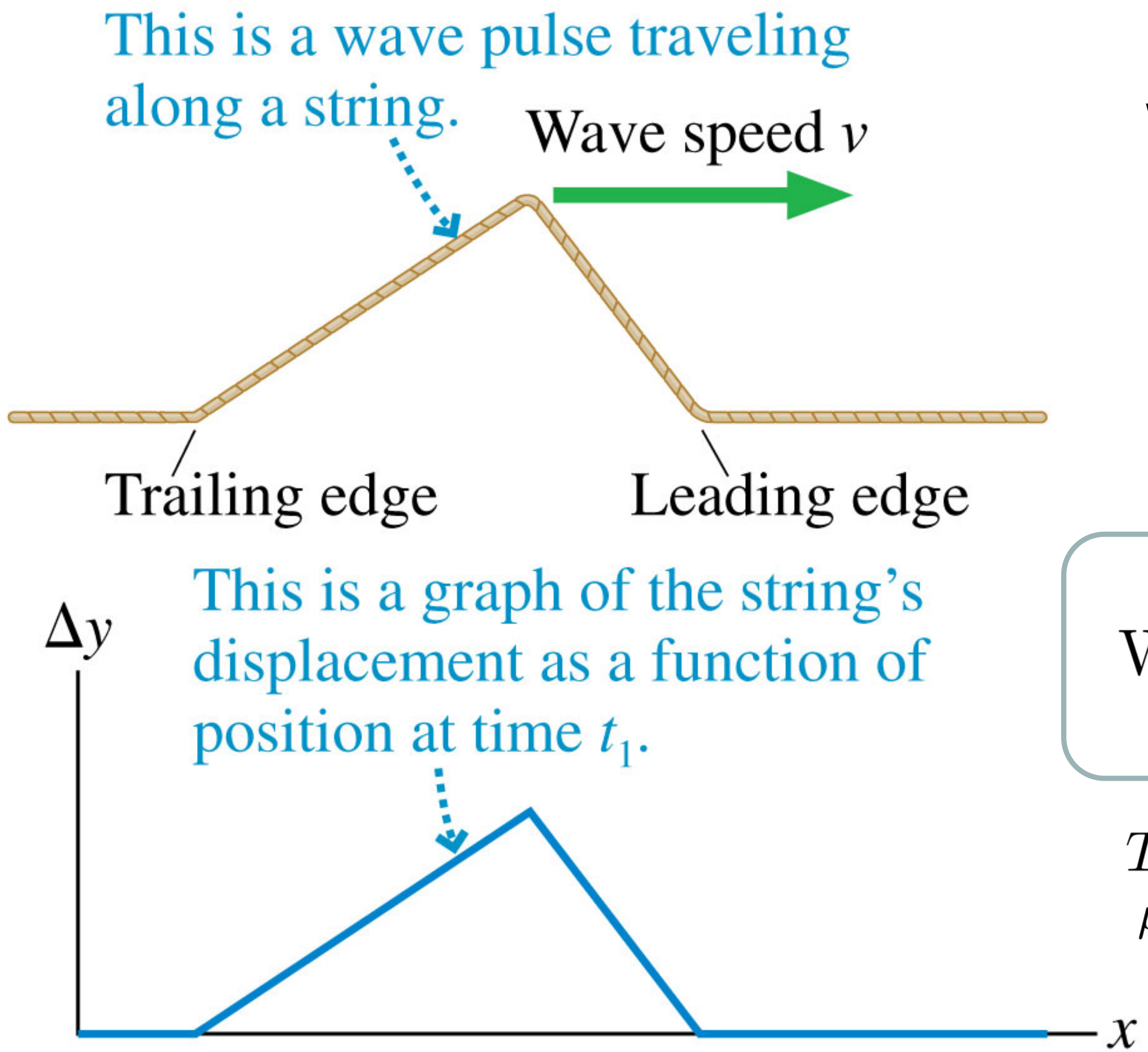
Let's watch a video…

"Medium" through which wave moves? PEOPLE
Note: Wave speed is NOT equal to individual oscillator speed!
Q: What does the wave speed depend on?
A: Interconnectedness of oscillators and Inertia of each oscillator

Another example: Wave traveling along a String



From previous slide:
Wave speed increases with interconnectedness between particles and decreases with mass of each particle

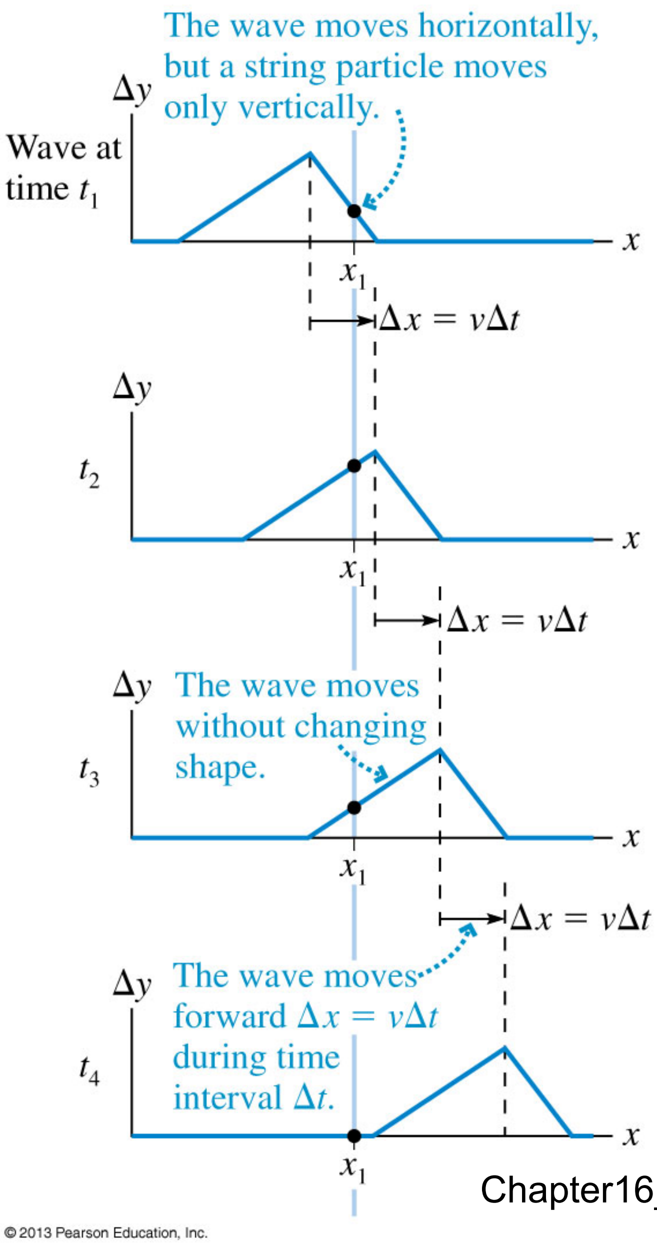
Sec. 16.1

$$\text{Wave Speed, } v = \sqrt{\frac{T_s}{\mu}}$$

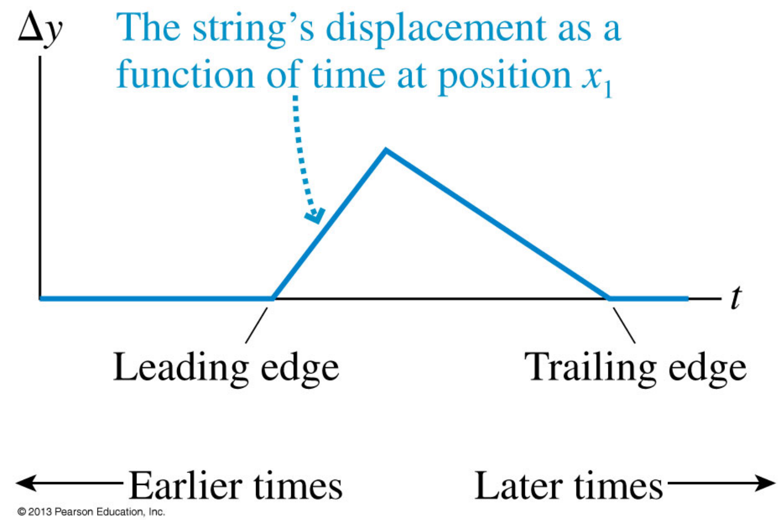
T_s = Tension in the string
μ = linear mass density of the string (mass/length)

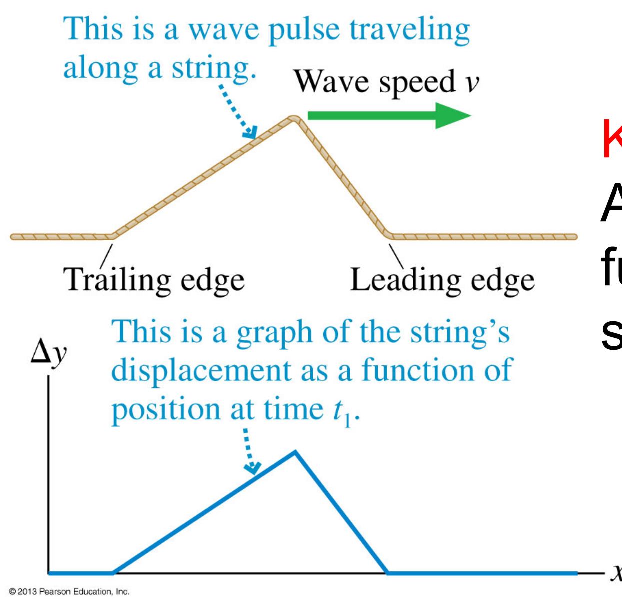
SEC 16.2 Two ways to picture Waves – the Snapshot & the History Graph

Snapshots



History Graph





KEY POINT 2!
A wave is a function of space *and* time.

$$\Delta y = f(x,t)$$

SEC 16.2…CONTINUED

So what do we do now? Well, we want to CONTROL waves, make waveforms of shapes we choose, modulate them at will Note that we can see stadium waves, slinky waves, water waves, but can't see sound waves, light waves, earthquake waves. Mechanical models of waves we can't see are sometimes useful.

Price to pay! Learn mathematical description of waves!!

Note that, for both the transverse and the longitudinal cases, the wave is a function of *both* space and time.

Mathematical Description of Waves starts by reminding ourselves of the FOURIER THEOREM

Essence of Fourier Theorem:

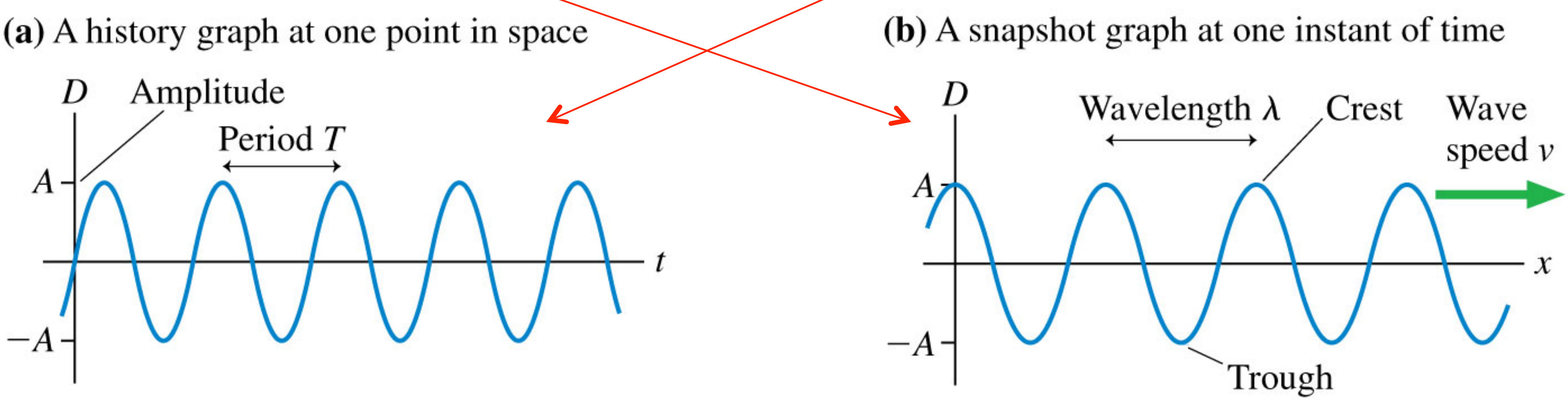
Any oscillation of any frequency can be written as a sum of many sinusoidal oscillations.

Therefore, sinusoidal oscillations and waves are important! [Sec. 16.3]

Travelling Sinusoidal Wave

A sinusoidal (or harmonic) disturbance creates a sinusoidal travelling wave.

At a given time, this wave is a sine wave in space, and **at a given point in space**, a point has harmonic motion in time.



where D(x,t) is the general disturbance from the equilibrium state.
Note: it is a function of two variables.

"Fundamental Relation for Waves"

$$v = \frac{\lambda}{T} = \lambda f = \frac{\omega}{k}$$

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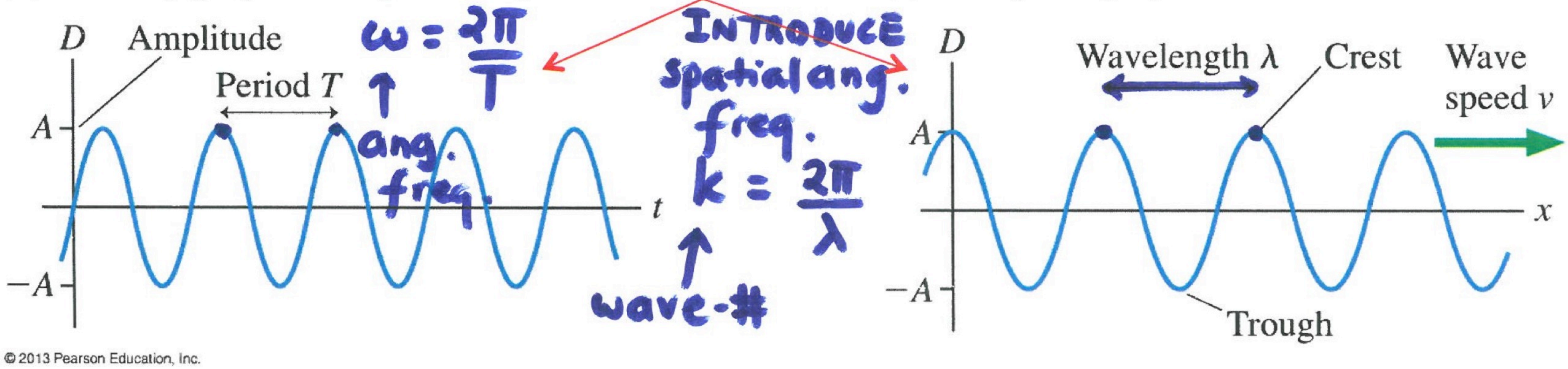
(a) A history graph at one point in space

(b) A snapshot graph at one instant of time



where D(x,t) is the general disturbance from the equilibrium state.
Note: it is a function of two variables. V = length of 1cycle (m) / time for 1cycle (s) = λ / T

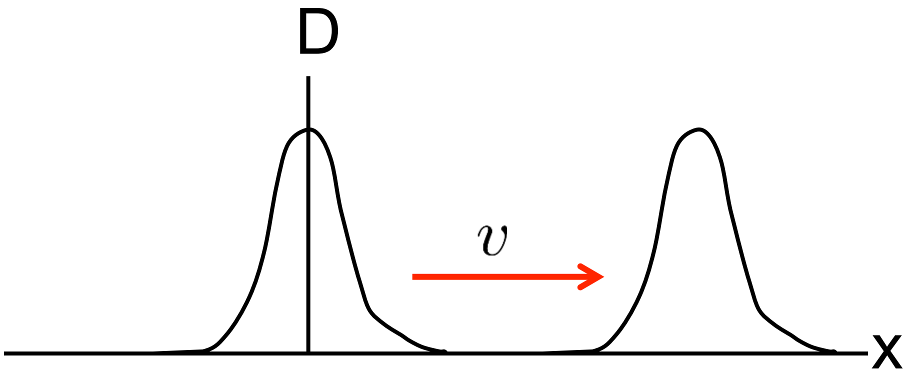
SINUSOIDAL

"Fundamental Relation for Waves"

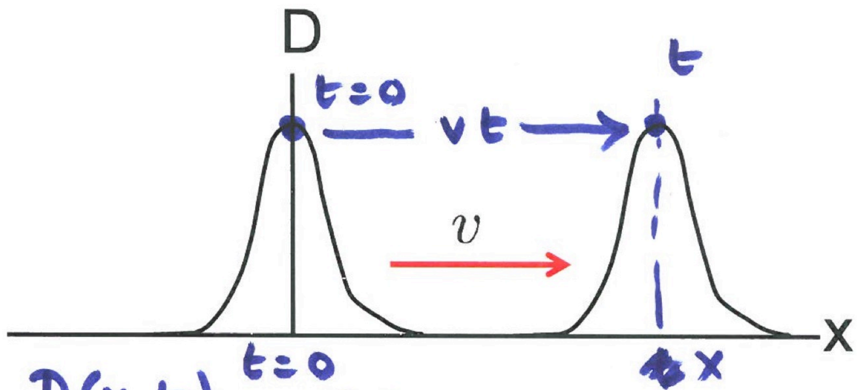
$$v = \frac{\lambda}{T} = \lambda f = \frac{\omega}{k} = \frac{2\pi f}{2\pi/\lambda} = f\lambda$$

NOT FORCE CONSTANT OF SPRING!!

$\Delta y = f(x,t)$ …but only a specific combination of x & t !!



$\Delta y = f(x,t)$ …but only a specific combination of x & t !!



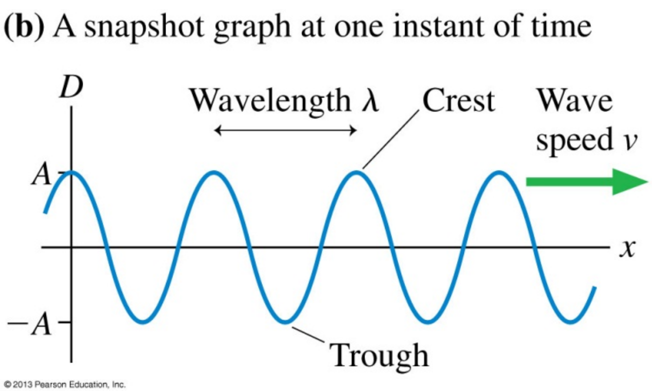
$v = f\lambda$
SINUSOIDAL WAVES

$D(x,t) = f(x,t)$

$f(x,t) = f(x - vt)$ PARTICULAR COMBINATION OF x, t

IMPORTANT ASIDE [If wave is traveling in opposite direction, replace 'v' w/ '$-v$'!
So, in that case, $f(x,t) = f(x + vt)$

Sec. 16.3 The Equation of Travelling Sinusoidal Wave



$A =$ Amplitude (displacement from undisturbed state)

$v =$ wave speed

$\lambda =$ Wavelength (distance for disturbance to repeat)

$T =$ Period (time for disturbance to repeat)

$f =$ Frequency $= \frac{1}{T}$

General Equation of a sinusoidal travelling wave:

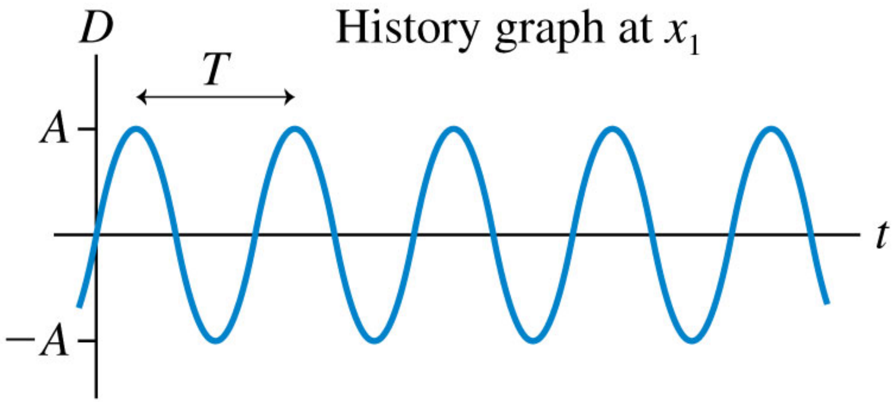
$$D(x,t) = A\sin(kx - \omega t + \phi_0)$$ **Travelling in +x direction**

$$D(x,t) = A\sin(kx + \omega t + \phi_0)$$ **Travelling in -x direction**

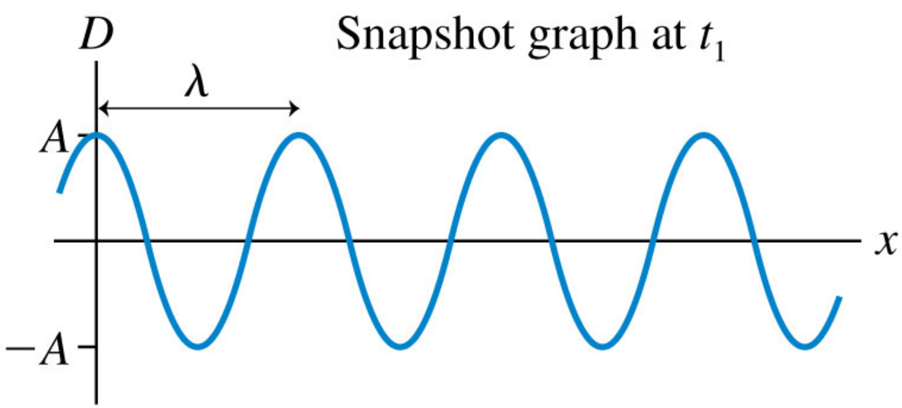
$k =$ Wave Number $= \frac{2\pi}{\lambda}$ [Units $= m^{-1}$] ***(watch the k's !)***

$\omega =$ Angular Freqency $= 2\pi f$

$\phi_0 =$ phase constant



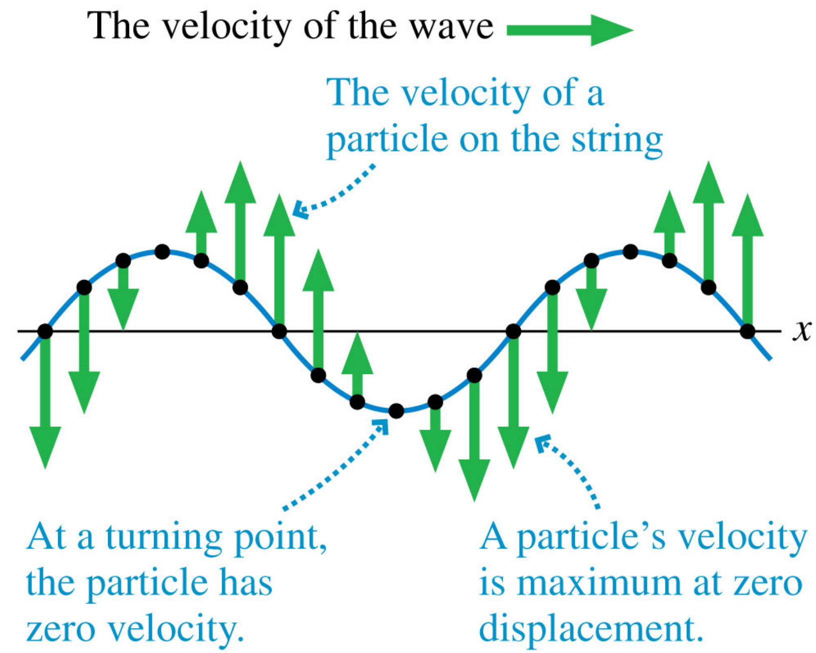
If x is fixed, $D(x_1, t) = A\sin(kx_1 - \omega t + \phi_0)$ gives a sinusoidal history graph at one point in space, x_1. It repeats every T s.



If t is fixed, $D(x, t_1) = A\sin(kx - \omega t_1 + \phi_0)$ gives a sinusoidal snapshot graph at one instant of time, t_1. It repeats every λ m.

KEY POINT 3

Note that "wave speed" is distinctly different from the "speed of the individual oscillators"!



Q: What *is* the speed of the individual oscillators?
A: Simple. The speed depends upon the x-location of the oscillator, and the time t, and is simply given by the derivative with respect to time of the wave, i.e.,

$$\frac{\partial D(x,t)}{\partial t} = -\omega A\cos(kx - \omega t + \phi_0)$$

Whiteboard Problem 1

The displacement of a wave traveling in the positive x-direction is $D(x, t) = (3.5\ \text{cm})\sin(2.7x - 124t)$, where x is in m and t is in s. What are the (a) frequency, (b) wavelength, and (c) speed of this wave?

d) What is D at x = 5.2m and t = 3.6s? [SET CALCULATOR TO RADIANS!!]

e) What is the speed of the oscillator located at x = 2 m at t = 3 s?

Whiteboard Problem 1

12. | The displacement of a wave traveling in the positive x-direction is $D(x, t) = (3.5 \text{ cm}) \sin(2.7x - 124t)$, where x is in m and t is in s. What are the (a) frequency, (b) wavelength, and (c) speed of this wave?

A, $k = \frac{2\pi}{\lambda}$, $\omega = 2\pi f = \frac{2\pi}{T}$

d.) What is D at x = 5.2m and t = 3.6s?

e) What is the speed of the oscillator located at x = 2m at t = 3 sec?

a) $\omega = 124 \text{ rad s}^{-1} \Rightarrow f = \frac{\omega}{2\pi} = \frac{124}{2\pi} = 19.7 \text{ Hz}$

b) $\lambda = \frac{2\pi}{k} = \frac{2\pi}{2.7} = 2.33 \text{ m}$

c) $v = f\lambda = (19.7)(2.33) = 46 \text{ m/s}$

d) $D = (3.5 \text{ cm}) \sin(2.7 \times 5.2 - 124 \times 3.6) = 3.24 \text{ cm}$

e) $\left.\frac{\partial D}{\partial t}\right|_{(x,t)} = -124 \left(\frac{3.5}{\text{cm}}\right) \cos(2.7x - 124t) \Big|_{x = 2\text{ m},\ t = 3\text{ s}} = 2.47 \text{ m/s}$

Whiteboard Problem 2

Write the displacement equation for a sinusoidal wave that is traveling in the negative *y*-direction with wavelength 50 cm, speed 4.0 m/s, and amplitude 5.0 cm. Assume $\phi_0 = 0$.

Whiteboard Problem 2

Write the displacement equation for a sinusoidal wave that is traveling in the negative y-direction with wavelength 50 cm, speed 4.0 m/s, and amplitude 5.0 cm. Assume $\phi_0 = 0$.

$$D(y,t) = A\sin(ky + \omega t + \phi_0)$$

$k \to 4\pi$, $\phi_0 \to 0$

$$\omega = 2\pi f = 2\pi \frac{v}{\lambda} = \frac{2\pi(4)}{0.5} = 16\pi \text{ rad s}^{-1}$$

$$k = \frac{2\pi}{\lambda} = \frac{2\pi}{0.5} = 4\pi \text{ rad/m}$$

$$D(y,t) = (5\text{ cm})\sin(4\pi y + 16\pi t)$$

Sec. 16.3…contd…Wave Phase

For any sinusoidal wave (e.g. 1D):

$$D(x,t) = A\sin(\underbrace{kx - \omega t + \phi_0}_{\text{wave ``phase'', } \phi})$$

Don't confuse the wave phase, ϕ, with the phase constant, ϕ_0. ϕ_0 gives the phase at $x = t = 0$.

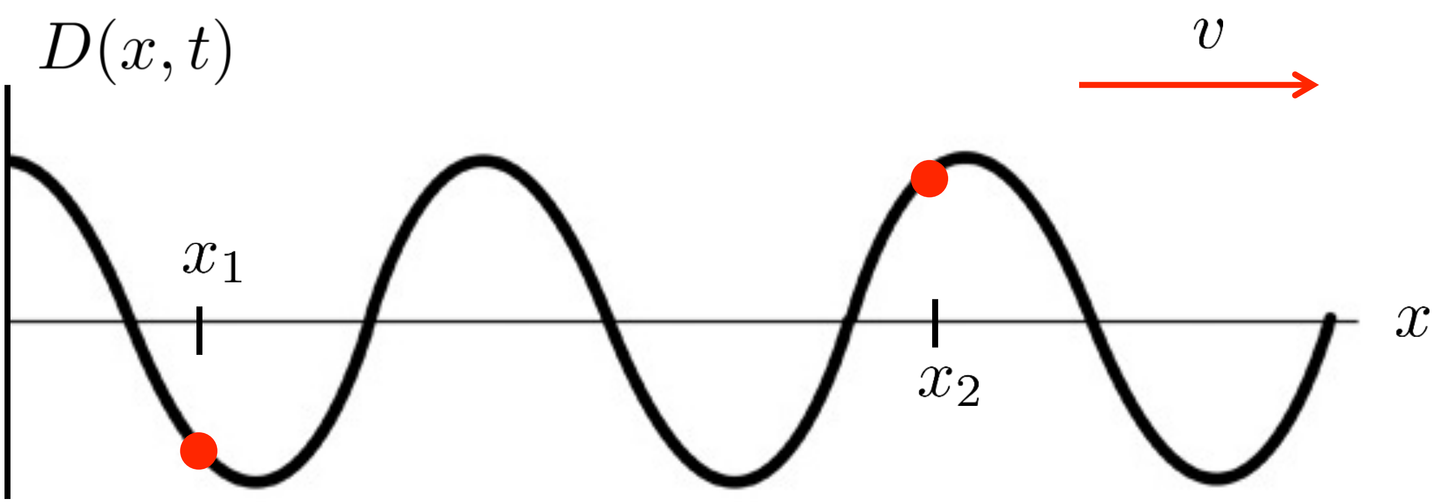
The wave phase determines where you are on the wave, i.e. a peak or trough, or somewhere in between.

In chapter 17, we'll look at combining waves, and the difference in phase will be very important.

Sec 16.3 The concept of "Phase Difference" in sinusoidal waves

Phase Difference Between Two Points at the Same Time (i.e., in a Snapshot)

Consider a 1D single wave travelling to the right at some time t:



Phase difference between points 1 and 2:

$$\Delta\phi = \phi_2 - \phi_1 \;= (kx_2 - \omega t + \phi_0) - (kx_1 - \omega t + \phi_0)$$
$$= k(x_2 - x_1) \;= \frac{2\pi}{\lambda}(x_2 - x_1)$$

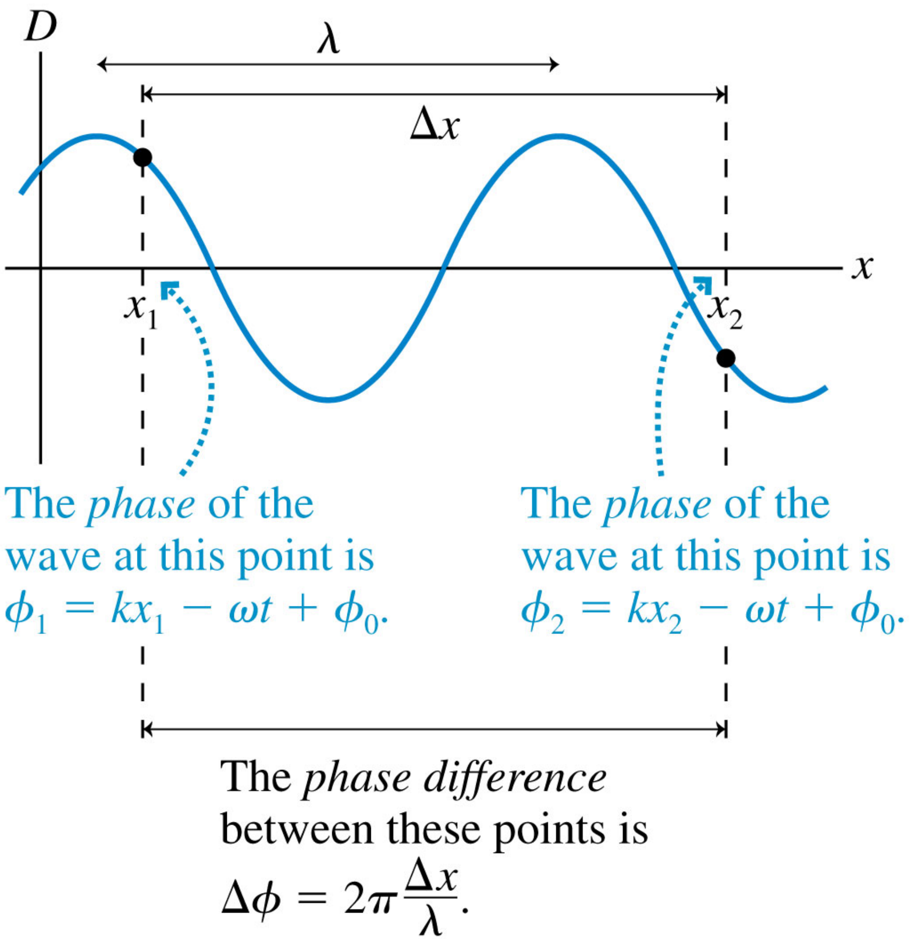
$\text{Note for: } x_2 - x_1 = \lambda \Rightarrow \Delta\phi = 2\pi$ (1 full cycle)

$x_2 - x_1 = \frac{\lambda}{2} \Rightarrow \Delta\phi = \pi$ (1/2 cycle)

Sec 16.3 The concept of "Phase Difference" in sinusoidal waves

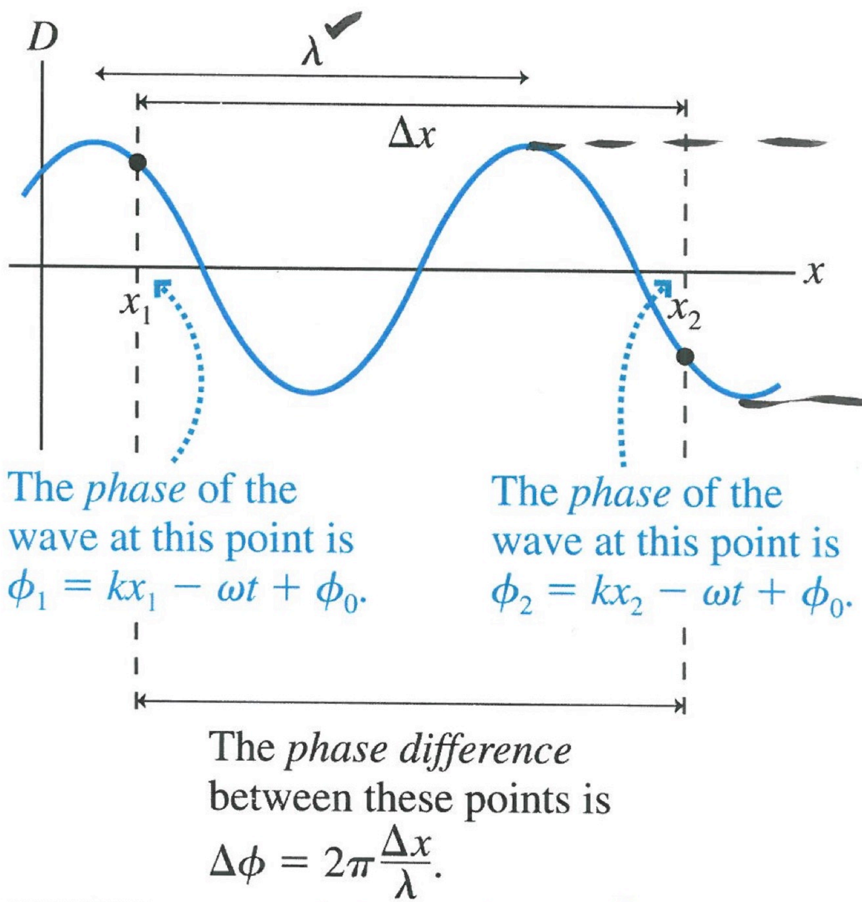
Phase Difference in the Snapshot

Phase Difference in the History graph



The concept of “Phase Difference” in sinusoidal waves

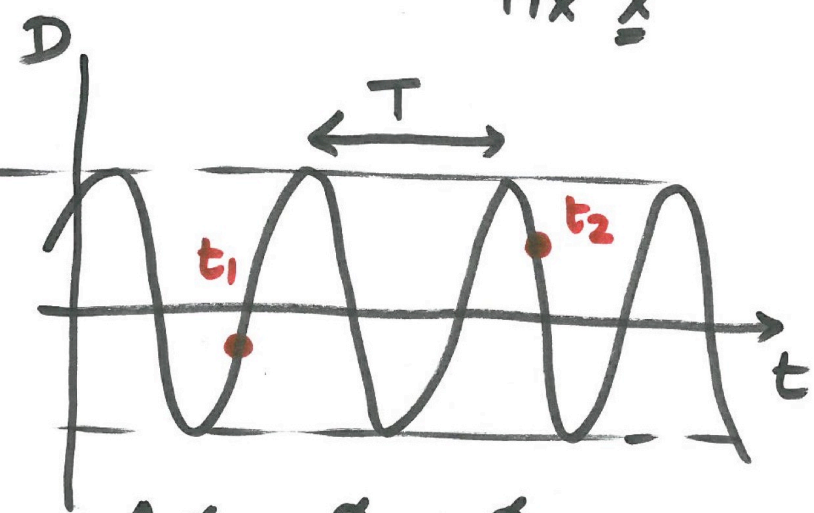
Phase Difference in the Snapshot



e.g. KEEP IN MIND WHEN WE DISCUSS “YOUNG'S (2-SLIT) INTERFERENCE PATTERN”

Phase Difference in the History graph

FIX 'x'

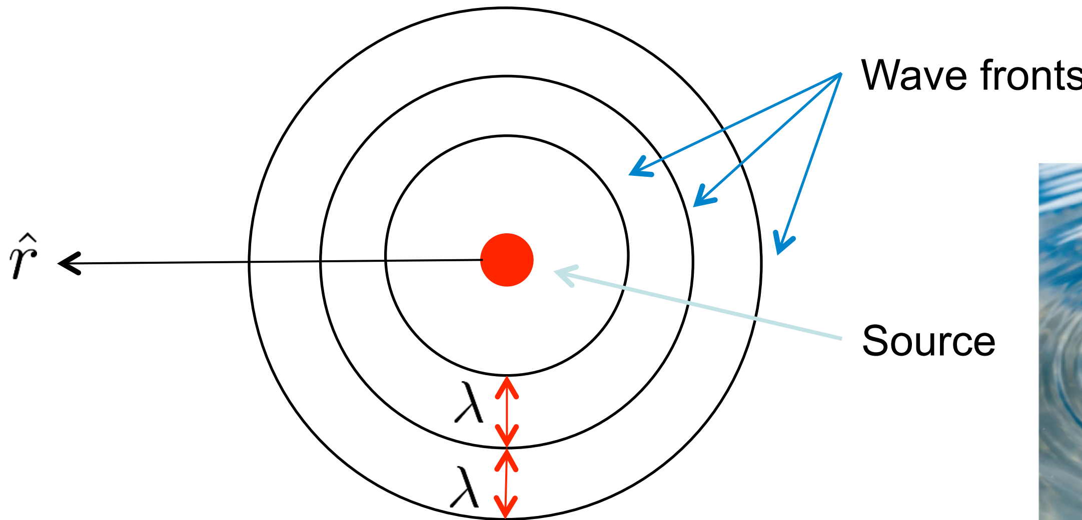


$$\Delta\phi = \phi_2 - \phi_1$$
$$= (kx - \omega t_2 + \phi_0) - (kx - \omega t_1 + \phi_0)$$
$$\Delta\phi = \omega(t_1 - t_2)$$

e.g. KEEP IN MIND WHEN WE DISCUSS “BEATS”

SKIP SEC. 16.4, 16.6

Sec. 16.7: Waves in 2 and 3 Dimensions



waves on a pond

In 2D or 3D, the amplitude of the wave will decrease since the energy is spread out over a larger circle (in 2D) or a sphere (in 3D). So a sinusoidal wave looks like:

$$D(r,t) = A(r)\sin(kr - \omega t + \phi_0)$$

Note: this is for an outgoing wave.

Whiteboard Problem 3

A spherical wave with a wavelength of 2.0 m is emitted from the origin. At one instant of time, the phase at $r = 4.0$ m is π rad. At that instant, what is the phase at $r = 3.5$ m and at $r = 4.5$ m?

Whiteboard Problem 3

A spherical wave with a wavelength of 2.0 m is emitted from the origin. At one instant of time, the phase at $r = 4.0$ m is π rad. At that instant, what is the phase at $r = 3.5$ m and at $r = 4.5$ m?

$$\Delta\phi = \phi_2 - \phi_1 = \frac{2\pi}{\lambda}(r_2 - r_1)$$

$r_2 = 3.5$ m; $r_1 = 4$ m

$$\phi_2 - \pi = \frac{2\pi}{2}(3.5 - 4)$$

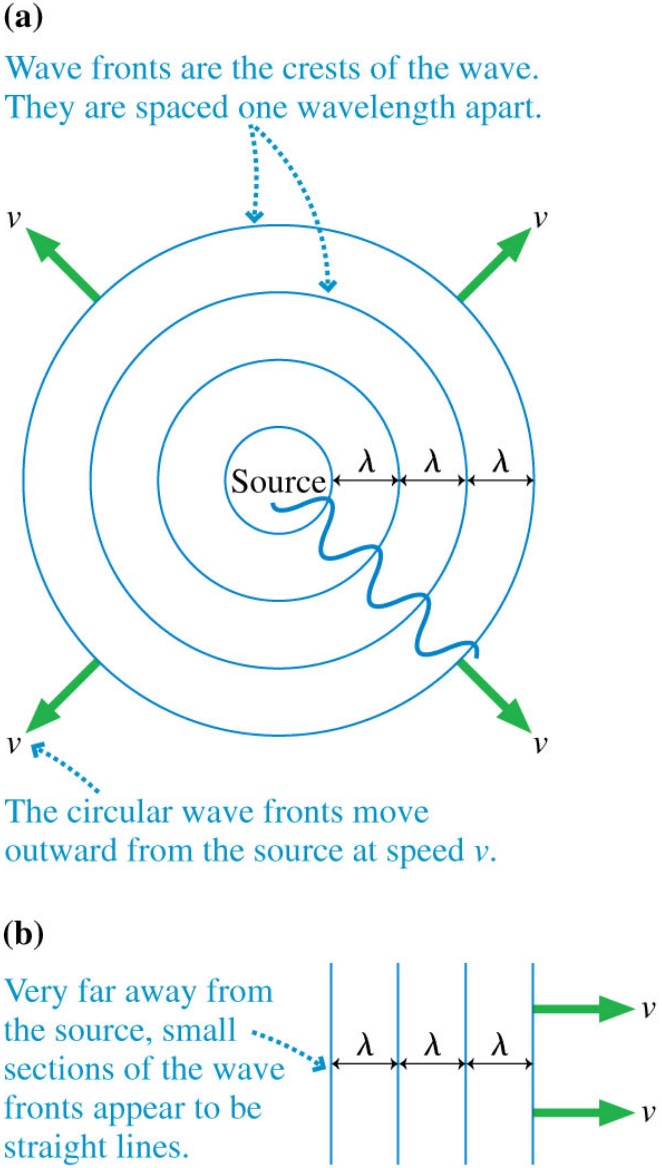
$$\Rightarrow \phi_2 = \pi[1 + 3.5 - 4] = 0.5\pi$$

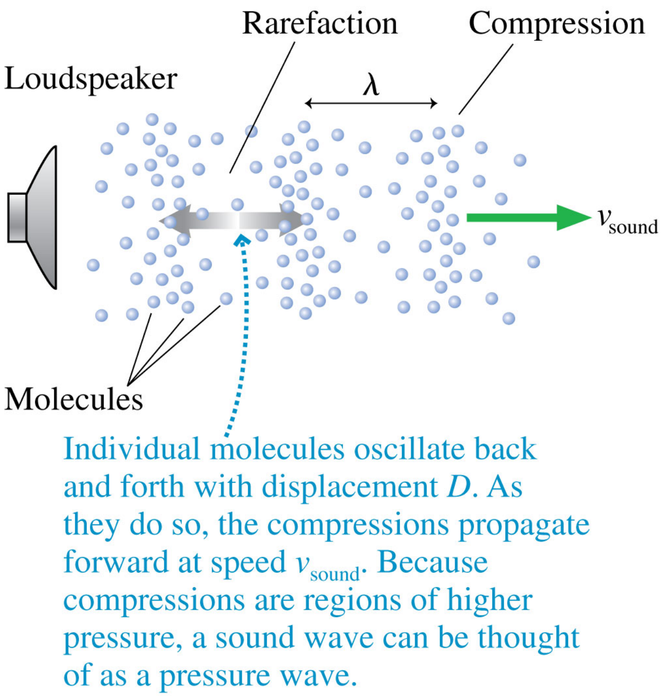
$r_2 = 4.5$ m; $r_1 = 4$ m

$$\phi_2 - \pi = \frac{2\pi}{2}(4.5 - 4)$$

$$\phi_2 = \pi[1 + 4.5 - 4] = 1.5\pi$$

SEC 16.7 CONCEPT OF "WAVEFRONTS":
Spherical and Planar Wavefronts for Transverse and Longitudinal Waves

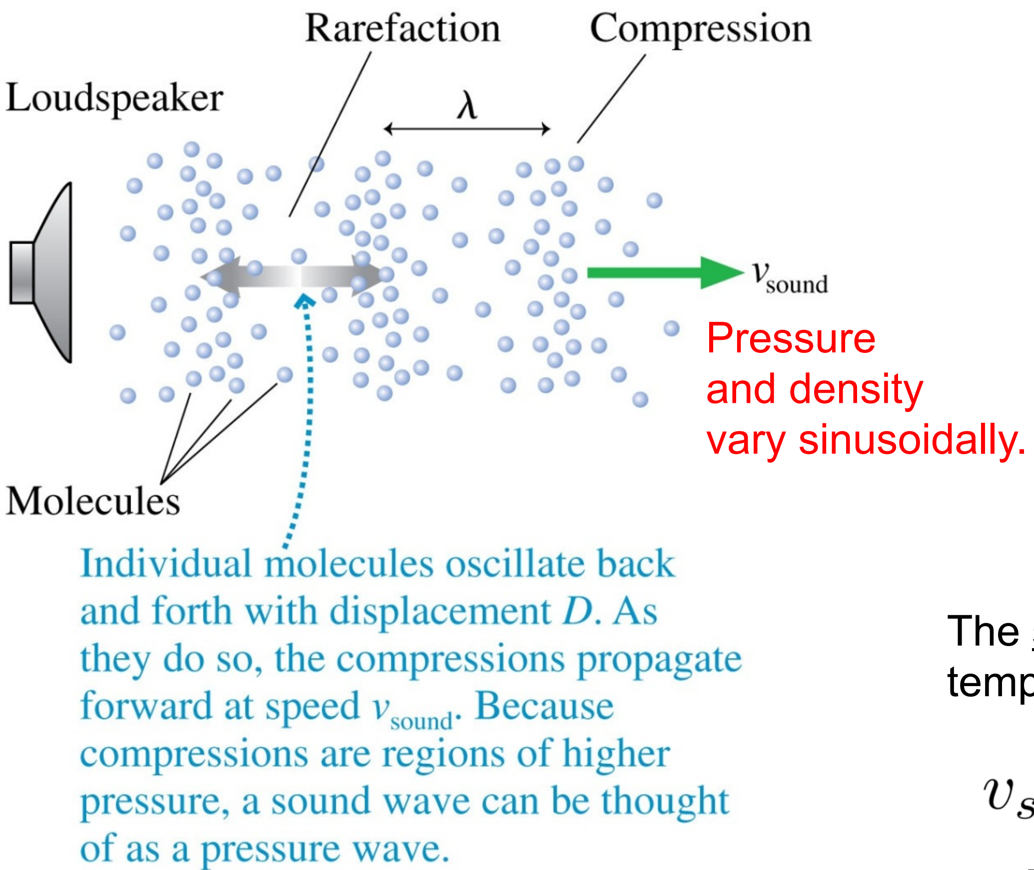




Sec. 16.5: Sound Waves

Sound waves are longitudinal compression waves that propagate through a medium – gas, liquid, or solid.

Sound Waves in Air:



The speed of sound

Medium	Speed (m/s)
Air (0°C)	331
Air (20°C)	343
Helium (0°C)	970
Ethyl alcohol	1170
Water	1480
Granite	6000
Aluminum	6420

The **speed of sound** in a gas is slightly temperature dependent, for air we will use:

$$v_s \ (\text{at } T = 20°C) = 343 \ m/s$$

Human frequency audible range:

$$\sim 20 \ Hz \leq f \leq \ \sim 20 \ kHz$$

Have you ever breathed Helium from a balloon? Why does this happen?

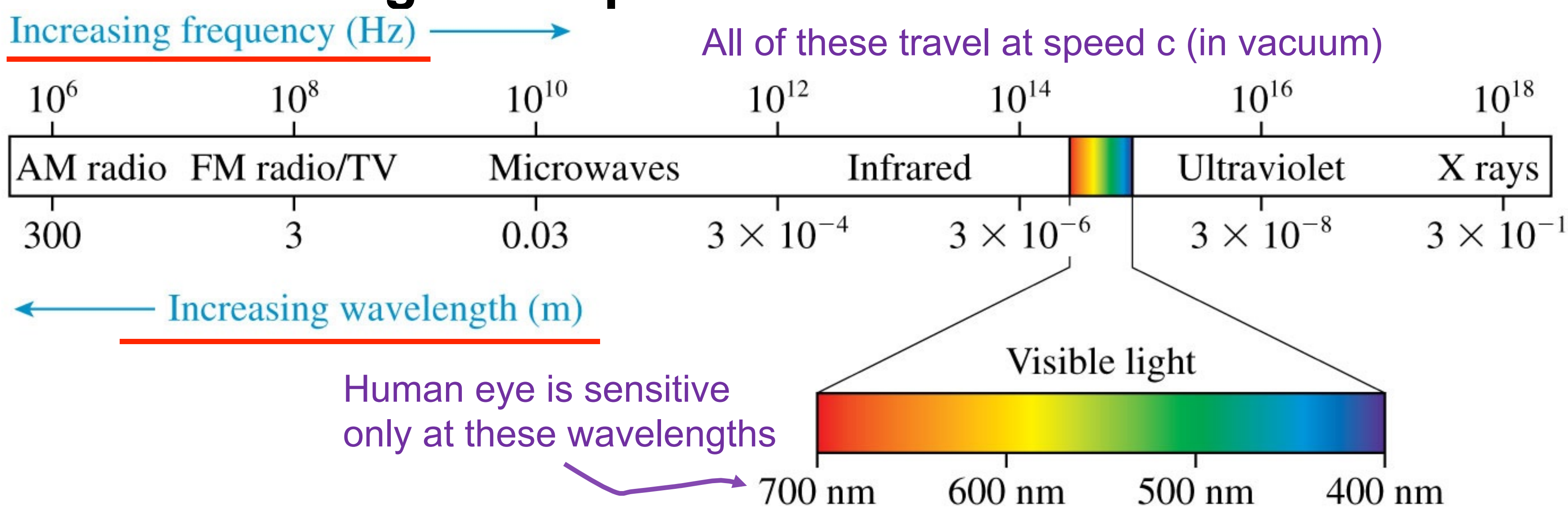
Helium in your vocal tract causes it to resonate at higher frequencies so those frequencies dominate what is emitted.

Sec. 16.5: Light, an Electromagnetic Wave

Light is a disturbance in the electromagnetic fields* created by oscillating electric charges. All electromagnetic waves propagate at:

$$\text{Speed of light in vacuum, } c = 3 \times 10^8 \; m/s$$

The Electromagnetic Spectrum:



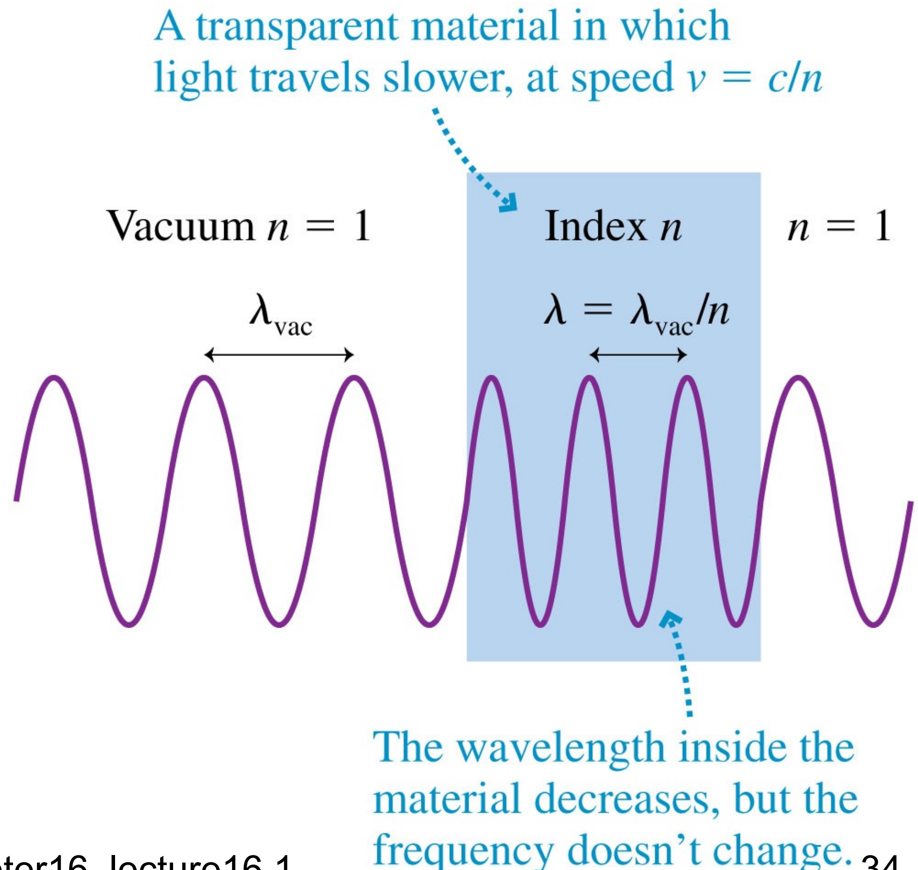
*There are actually two models of light that are used in physics. The Wave Model was discovered by Maxwell in the 1860's (we'll look at this in PHY192); however, in the early 20th century, it was realized that Maxwell's wave theory didn't work in the realm of atoms. As we'll see, this requires that light be viewed as a particle with wave properties or a wave with particle properties.

Sec. 16.5: Light, an Electromagnetic Wave

When light passes through a transparent medium*, it slows down. This Determines the medium's **index of refraction**:

$$\text{Index of Refraction, n} = \frac{\text{speed of light in Vac}}{\text{speed of light in medium}} = \frac{c}{v}$$

When entering a medium, the speed of the wave changes, but the frequency remains the same. Thus the wavelength must change:



*This happens for other types of waves too.

Light, an Electromagnetic Wave

When light passes through a transparent medium*, it slows down. This Determines the medium's **index of refraction**:

e.g. glass, $n = 1.5$; water, $n = 1.33$

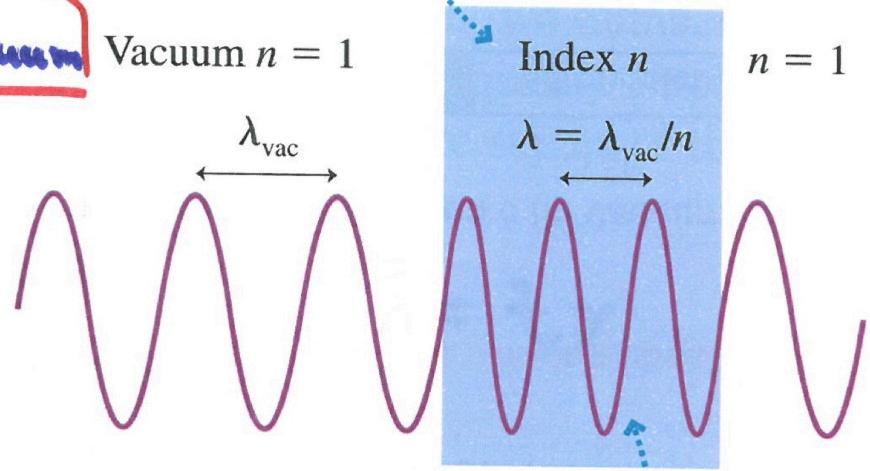
$$\text{Index of Refraction, } n \equiv \frac{\text{speed of light in Vac}}{\text{speed of light in medium}} = \frac{c}{v} \Rightarrow v = c/n$$

$c \rightarrow 3 \times 10^8$ m/s

$v = f\lambda$

$$f = \frac{v}{\lambda} = \frac{c/n}{\lambda_{medium}} = \frac{c}{\lambda_{vacuum}}$$

A transparent material in which light travels slower, at speed $v = c/n$



When entering a medium, the speed of the wave changes, but the frequency remains the same. Thus the wavelength must change:

$$\lambda_{medium} = \frac{\lambda_{vacuum}}{n}$$

The wavelength inside the material decreases, but the frequency doesn't change.

*This happens for other types of waves too.

Whiteboard Problem 4

Cell phone conversations are transmitted by high-frequency radio waves. Suppose the signal has wavelength 35 cm while traveling through air. What are the
(a) frequency and (b) wavelength as the signal travels through 3-mm-thick window glass into your room? (Refractive index of glass = 1.5)

An experiment set up in Samir's lab downstairs can create atomic vapor with a refractive index of 10^7 (!) using a phenomenon discovered in 1990 called "Electromagnetically Induced Transparency". *What is the speed of light through such a medium?*

Lene Hau was the 1st physicist to produce "slow light" in 1999 at Harvard U. Follow the links below to see two 3 min videos on her "slow light lab".
https://www.youtube.com/watch?v=EK6HxdUQm5s and
https://www.youtube.com/watch?v=-8Nj2uTZc10
Applications: Quantum Information storage and processing

Whiteboard problem 4

$$f_{vac} = f_{glass}$$

$$f_{vac} = c/\lambda$$

a)

$$c/\lambda = \frac{3\times 10^{10}\ \text{cm/s}}{35\ \text{cm}} = 8.6\times 10^{8}\ \text{Hz}$$

b)

$$\lambda_{glass} = \frac{v_{glass}}{f} = \frac{c/n}{f} = \frac{\frac{3\times 10^{10}}{1.5}}{8.6\times 10^{8}} = 23.3\ \text{cm}$$

$$v = c/n = \frac{3\times 10^{8}\ \text{m/s}}{10^{7}} = 30\ \text{m/s}$$

↓

atomic vapor

[Source: Natural History Magazine, March 1974]

	mph	m/s
Peregrine Falcon	200+	90+
Cheetah	70	31*
Horse	50	22
Domestic Cat	30	13
Grizzly Bear	30	13
Human	28	12**
Giant Tortoise	0.2	0.09

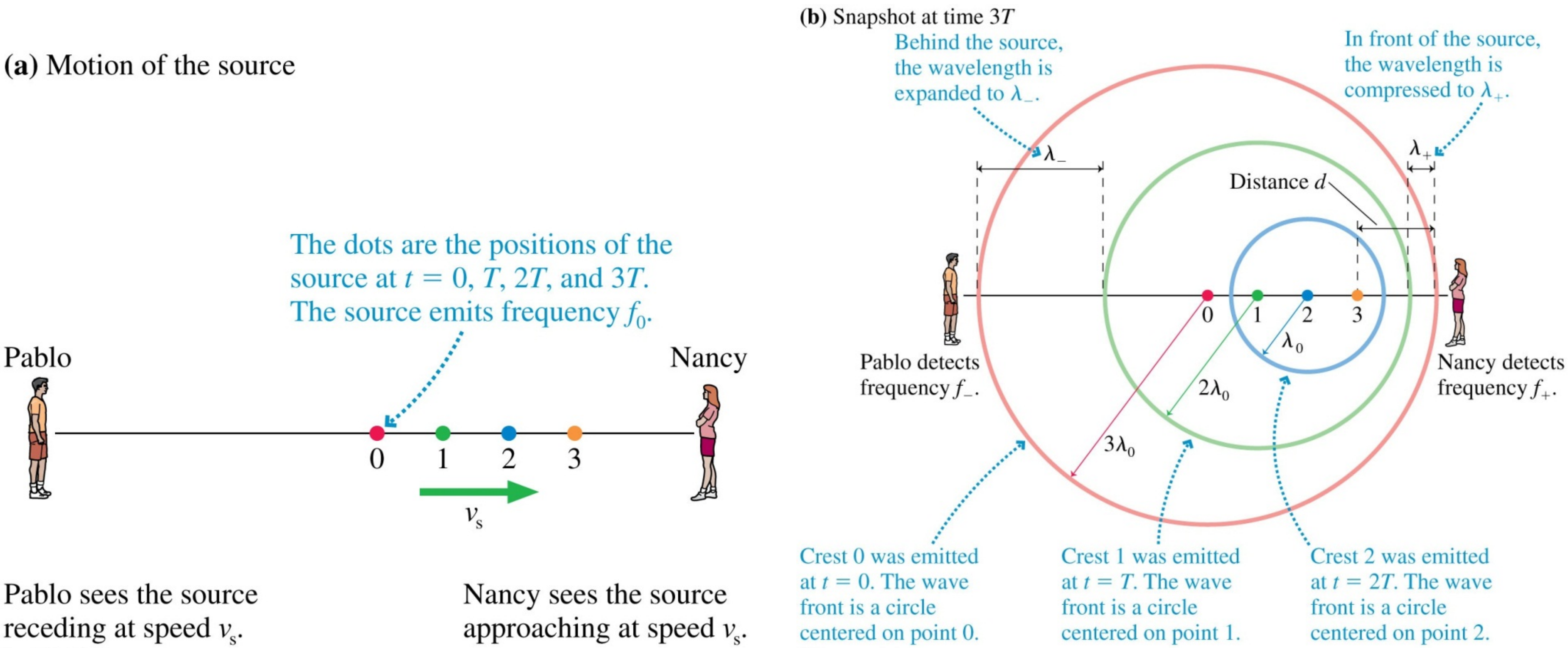
* measured over 100 yards

** measured over 15 yard segment of a 100 yard run!
Usain did 10.3 m/s at the World Championships.
You are not Usain.

Skip Sec. 16.8
Move on to Sec. 16.9: The Doppler Effect

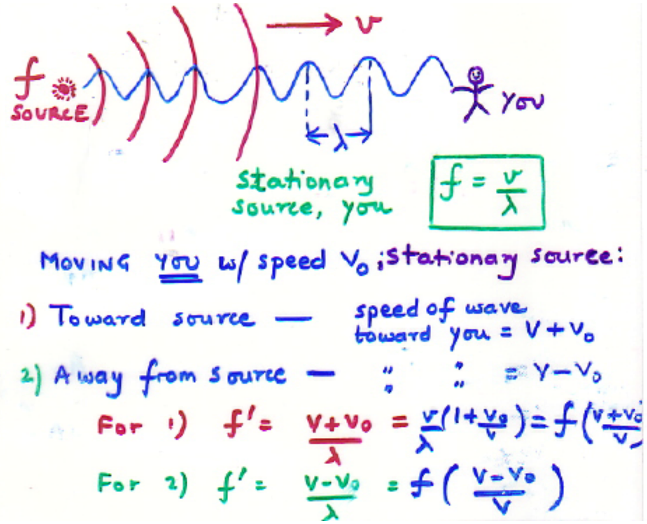
The Doppler Effect refers to a change in the perceived wavelength (or frequency) of a wave due to the motion of the source or the observer. It was discovered in the 1840's when it was first noticed for trains. Today, it still shows up in TV shows.

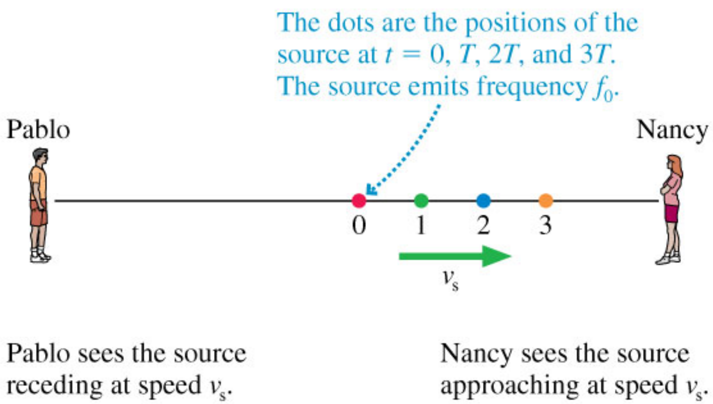
What causes the Doppler Effect?



SKIP SEC. 16.8, MOVE ON TO **SEC. 16.9** – THE DOPPLER EFFECT

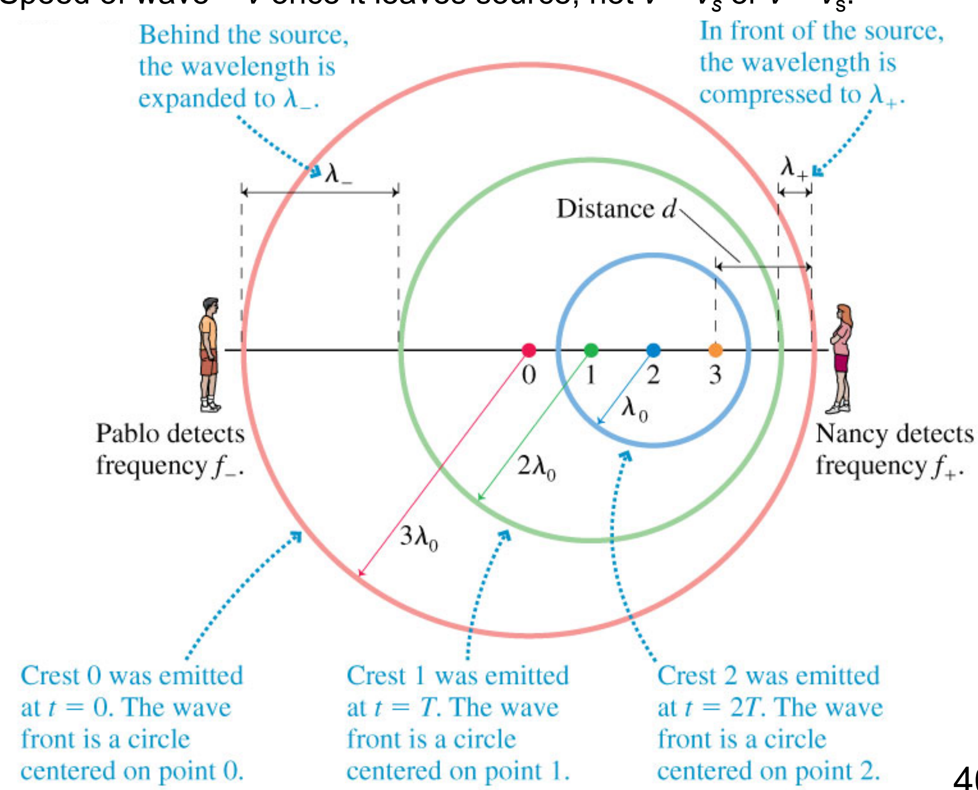
i) Moving observer

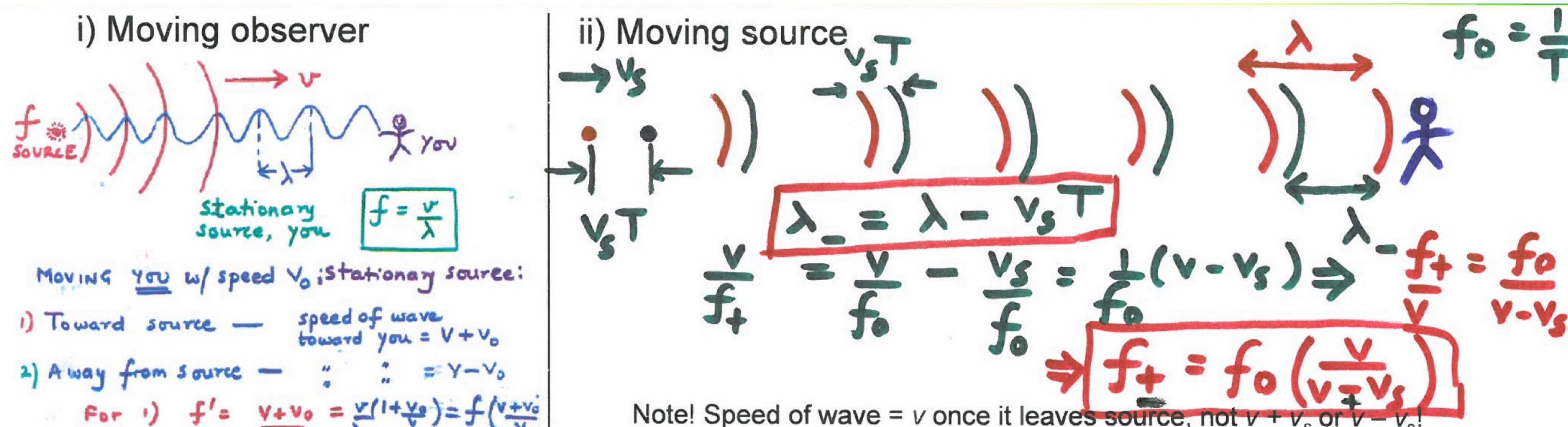


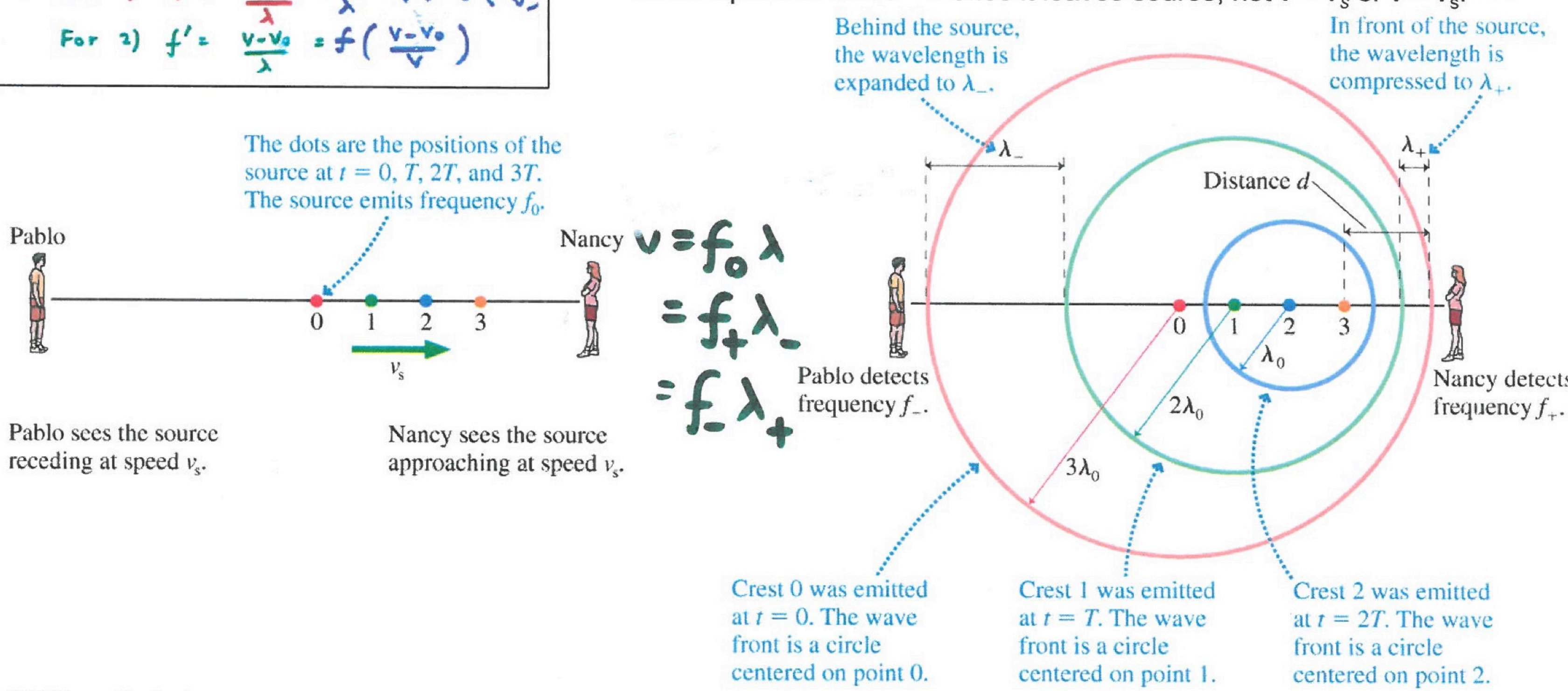


ii) Moving source

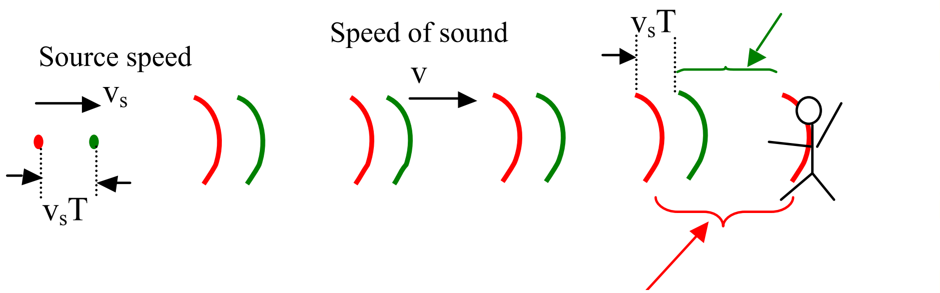
Note! Speed of wave = v once it leaves source, not $v + v_s$ or $v - v_s$!




i) Moving observer
v
f
SOURCE
YOU
λ
Stationary source, you
f = v/λ
MOVING YOU w/ speed V₀ ; stationary source:
1) Toward source — speed of wave toward you = V+V₀
2) Away from source — " " = V−V₀
For 1) f′ = (V+V₀)/λ = v(1+V₀/v)/λ = f((v+v₀)/v)
For 2) f′ = (V−V₀)/λ = f((V−V₀)/V)
ii) Moving source
Vs
VsT
λ
f₀ = 1/T
λ₋ = λ − VsT
λ₋
V/f₊ = V/f₀ − Vs/f₀ = 1/f₀ (V − Vs) ⇒ f₊/V = f₀/(V−Vs)
⇒ f₊ = f₀ (V/(V∓Vs))
Note! Speed of wave = v once it leaves source, not v + vs or v − vs!


Behind the source, the wavelength is expanded to λ₋.
In front of the source, the wavelength is compressed to λ₊.
The dots are the positions of the source at t = 0, T, 2T, and 3T. The source emits frequency f₀.
Pablo
Nancy
0 1 2 3
vs
v = f₀ λ
= f₊ λ₋
= f₋ λ₊
Pablo sees the source receding at speed vs.
Nancy sees the source approaching at speed vs.
λ₋
λ₊
Distance d
λ₀
2λ₀
3λ₀
Pablo detects frequency f₋.
Nancy detects frequency f₊.
Crest 0 was emitted at t = 0. The wave front is a circle centered on point 0.
Crest 1 was emitted at t = T. The wave front is a circle centered on point 1.
Crest 2 was emitted at t = 2T. The wave front is a circle centered on point 2.

λ' = "perceived" distance between crests if source is moving with velocity v_s



● OLD source position
● NEW source position

λ = distance between crests if source is stationary

You stationary, SOURCE MOVING TOWARD YOU:

$$\lambda' < \lambda$$

$$f = \frac{v}{\lambda} \text{ if source, you stationary}$$

$$\therefore f' = \frac{v}{\lambda'} \quad \text{i.e. } f' > f$$

$$\boxed{\lambda = vT = \frac{v}{f}}; \quad \lambda' = vT - v_sT = (v - v_s)T = \frac{v - v_s}{f}$$

$$\therefore f' = \frac{v}{\lambda'} = \left(\frac{v}{v - v_s}\right) f$$

You stationary, SOURCE MOVING AWAY FROM YOU:

$$\lambda' > \lambda, \quad f' < f$$

$$f' = \left(\frac{v}{v + v_s}\right) f$$

NOTE: DOPPLER EFFECT works for light waves too! Q: Is the Universe expanding?

Doppler shift chart for sound (for light use Eqns. 16.67)

"TOWARD" ⇒ increase in perceived frequency
"AWAY" ⇒ decrease " " "

① SOURCE TOWARD YOU, YOU TOWARD SOURCE:

$$f' = f\left(\frac{v + v_o}{v - v_s}\right)$$

② SOURCE TOWARD YOU, YOU AWAY FROM SOURCE:

$$f' = f\left(\frac{v - v_o}{v - v_s}\right)$$

③ SOURCE AWAY FROM YOU, YOU TOWARD SOURCE:

$$f' = f\left(\frac{v + v_o}{v + v_s}\right)$$

④ SOURCE AWAY FROM YOU, YOU AWAY FROM SOURCE:

$$f' = f\left(\frac{v - v_o}{v + v_s}\right)$$

All possible cases are indicated above

COOL APPLICATIONS OF DOPPLER EFFECT:

1) The Universe is expanding!

2) Slowing/cooling atoms using light – create the coldest matter in the Universe! (Use "Resonance" AND "Doppler effect") 1997 Nobel

Whiteboard Problem 5

A bat locates insects by emitting ultrasonic “chirps” and the listening for echoes from the bugs. Suppose a bat chirp has a frequency of 25 kHz. How fast would the bat have to fly, and in what direction, for you to just barely be able to hear the chirp at 20 kHz?

Whiteboard problem 5

$$f_{\pm} = f_0 \left(\frac{v}{v \mp v_s} \right)$$

$$(20\ \text{kHz}) = (25\ \text{kHz}) \left(\frac{343}{343 + v_s} \right)$$

$$\frac{20}{25} = \frac{343}{343 + v_s}$$

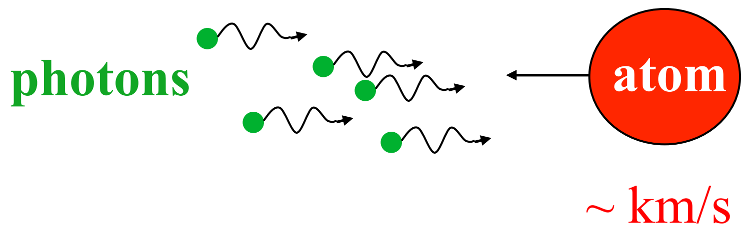
$$20(343 + v_s) = 343(25)$$

$$v_s = \frac{343(25-20)}{20} = 85.8\ \text{m/s}$$

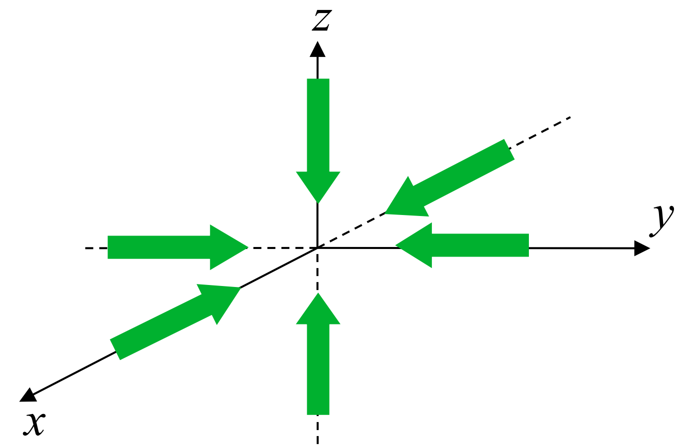
~ 180 mph!

Slowing/cooling atoms using light *(The 1997 Physics Nobel)*

"How to use Resonance and the Doppler Effect to do Nanotechnology"



Atoms may be moving in any direction…
…so shine photons from all directions!



Problem: Forces from
counter-propagating laser beams cancel!

Slowing/cooling atoms using light *(The 1997 Physics Nobel)*

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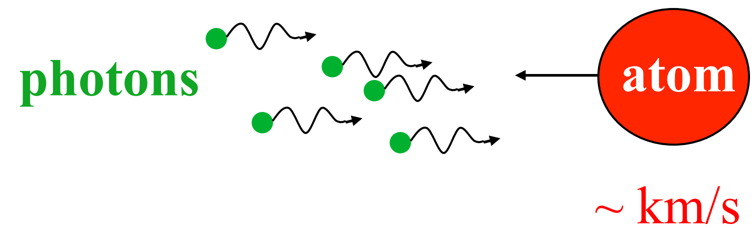
Natural frequency of electron oscillator = ω_0



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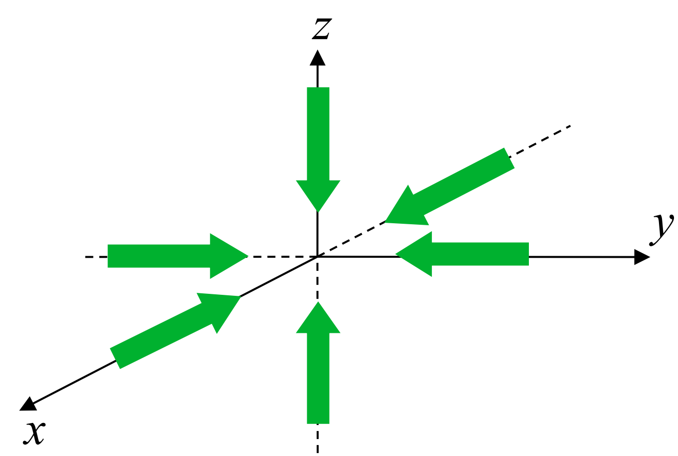

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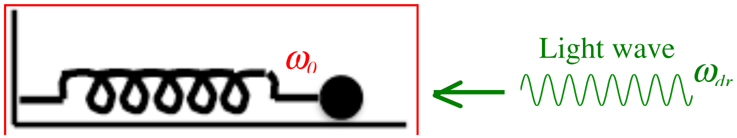

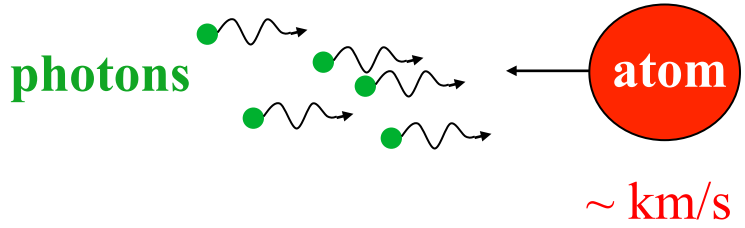

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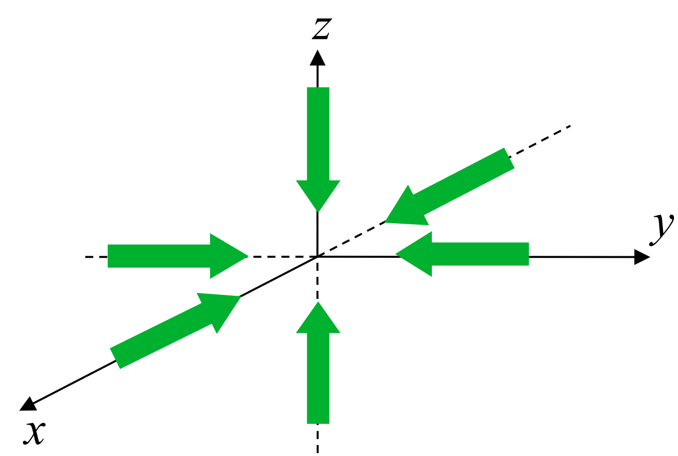

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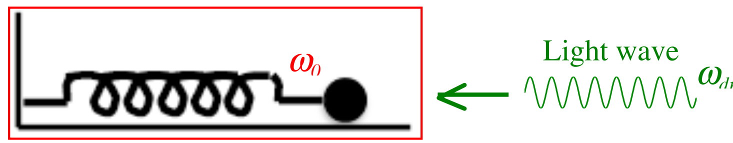
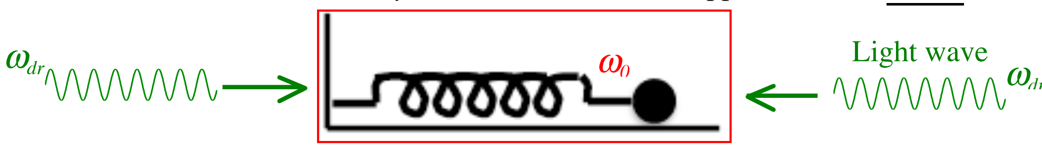
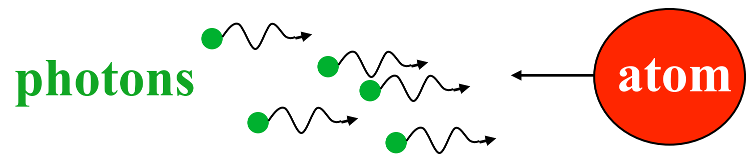


Concept 3: Electron oscillator maximally absorbs light wave (i.e., the atom feels the maximum force from the light) when $\omega_{dr} = \omega_0$ i.e., at resonance!
This is true for a *stationary* atom. But forces from opposite beams cancel.





~ km/s

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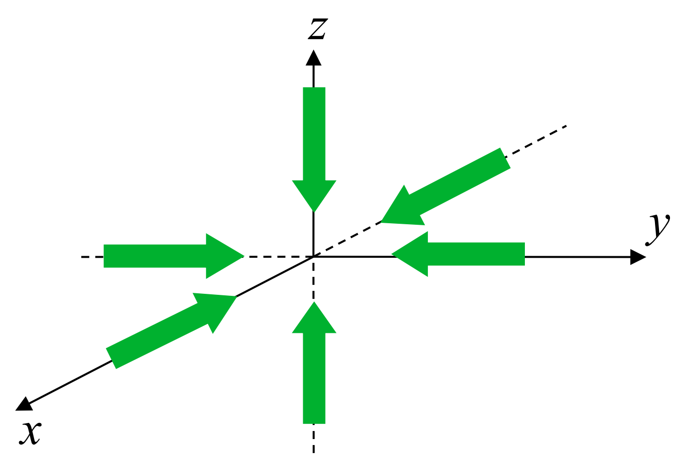

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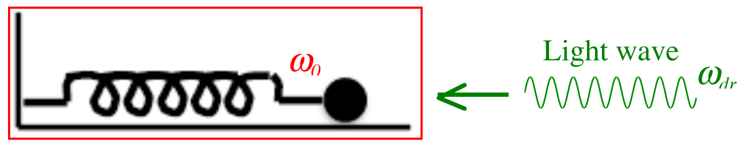

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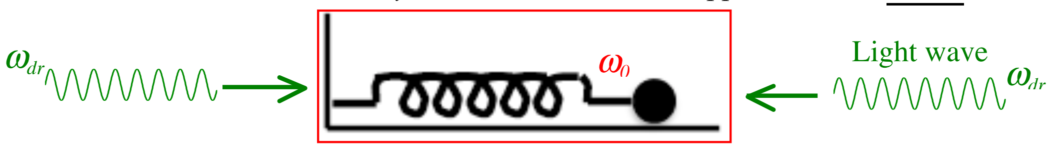
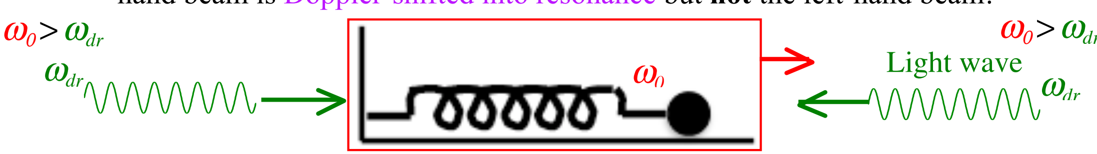
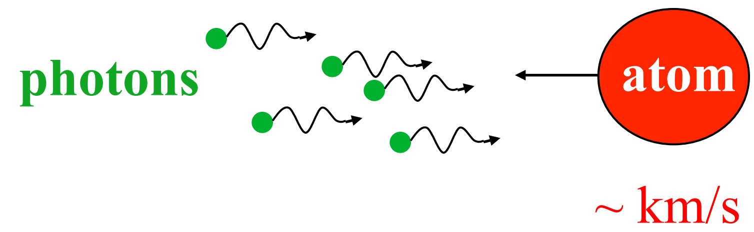


Concept 4: For a **moving** atom, say to the right, arrange $\omega_{dr} < \omega_0$. The right-hand beam is Doppler-shifted into resonance but **not** the left-hand beam!





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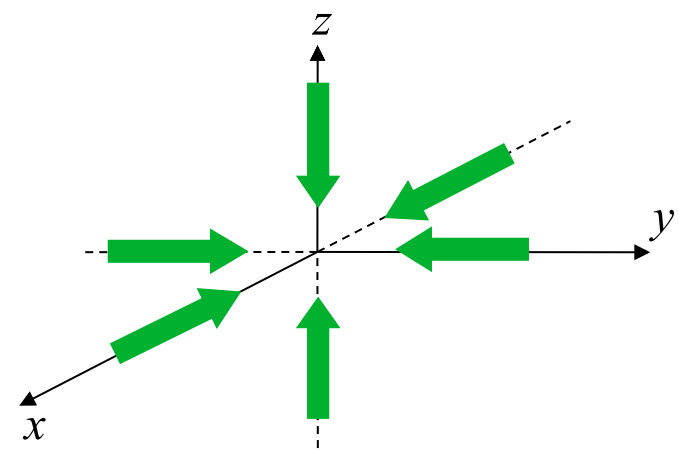

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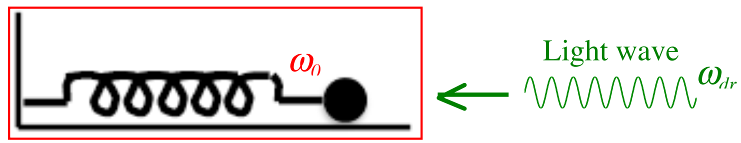

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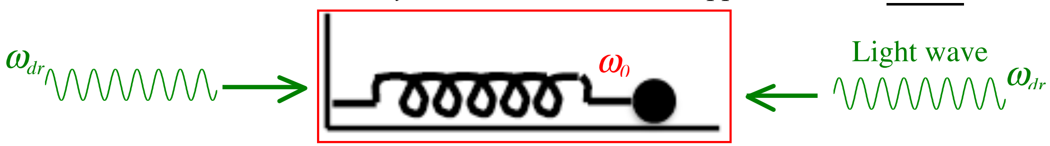

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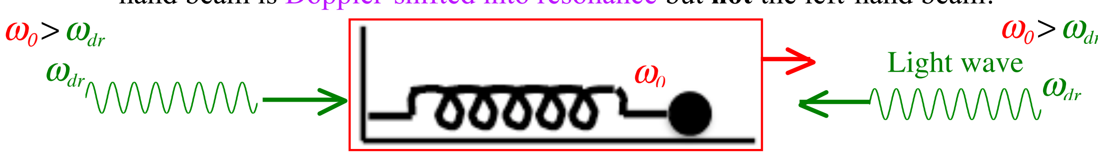
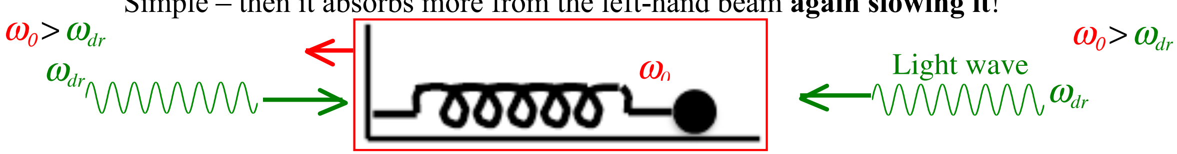
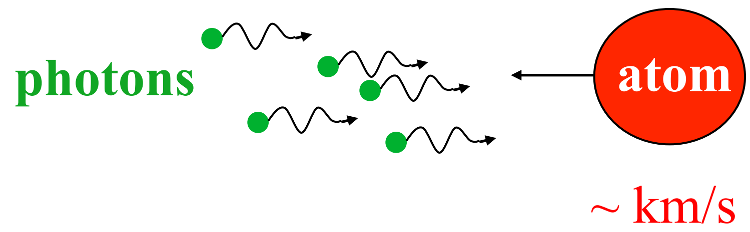


Concept 5: This moving atom absorbs more photons from the right-hand beam, thus feeling a net force to the left, hence **slowing the atom down**! But, what if the atom was moving to the left? Simple – then it absorbs more from the left-hand beam **again slowing it**!



Do this from all 6 directions…now the atoms have nowhere to go! They are slowed down in every direction…we have the slowest, the coldest atoms in the universe!!! Great building blocks for nanotechnology!!



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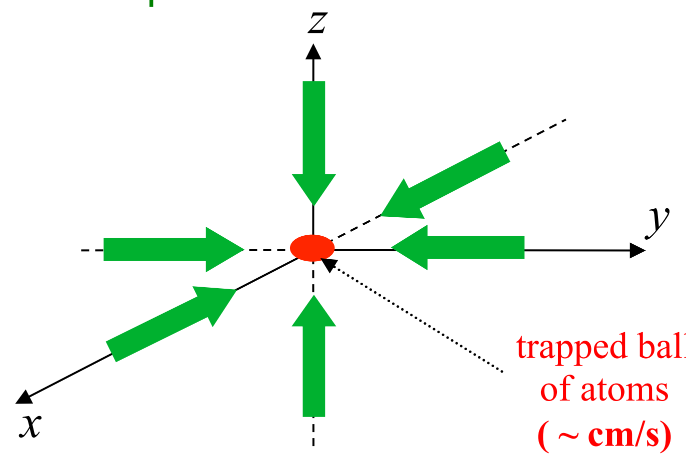
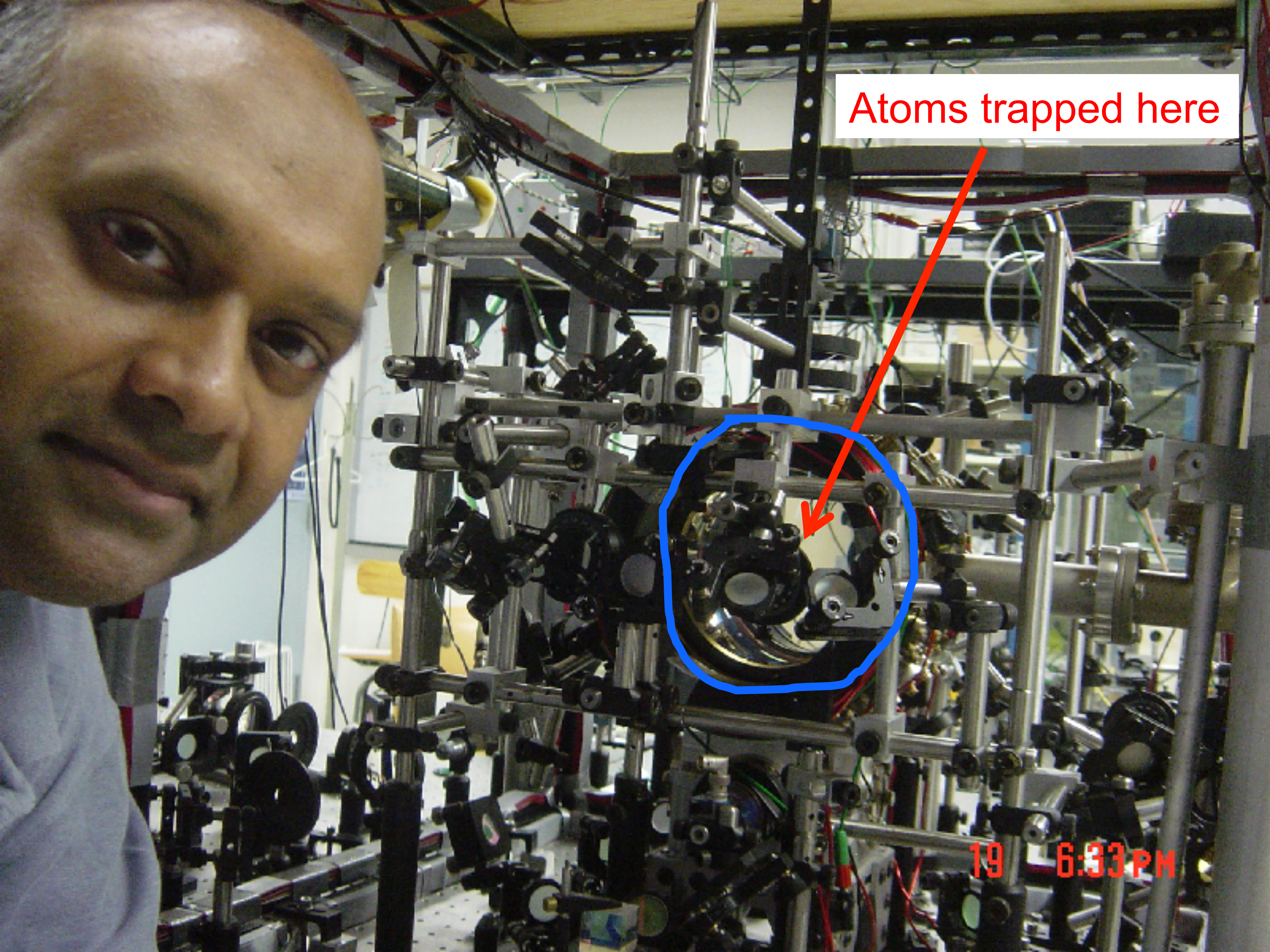


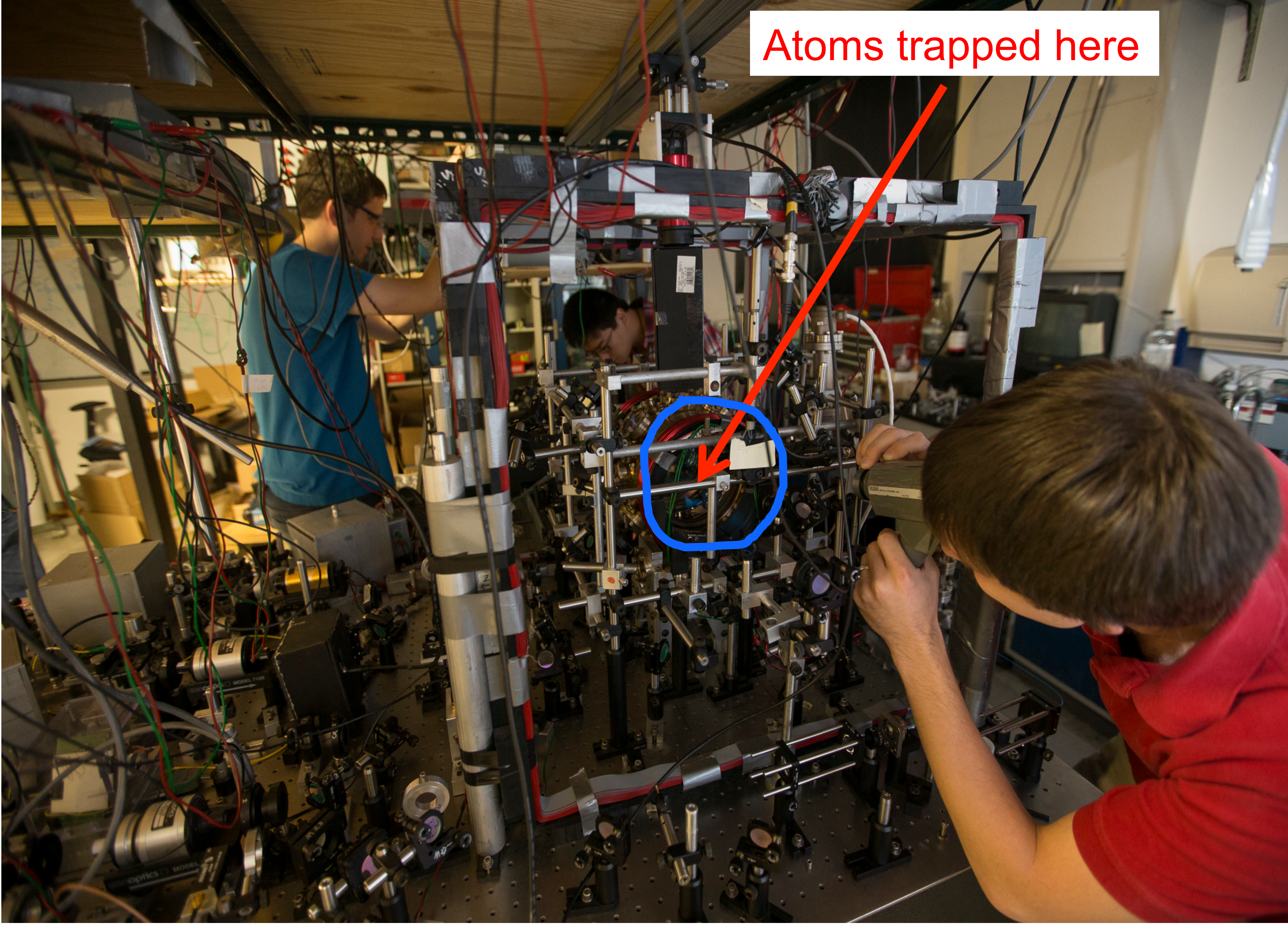
~~Problem: Forces from counter-propagating laser beams cancel!~~

COLDEST MATTER IN THE UNIVERSE

- ~10-100 million atoms in a 1-2 mm diameter ball
- Density: ~10^{10} atoms/cm^3
- T: 30 μK! Speed: 10 - 30 cm/s – **Nobel 1997**
- Matter Waves & Bose-Einstein condensation – **Nobel 2001**
- Quantum Optics / Atom Optics – **Nobel 2005**
- Quantum Information processing – **Nobel 2012**
- Nanolithography, Atom Lasers, Quantum Computers



Atoms trapped here
19 6:33PM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