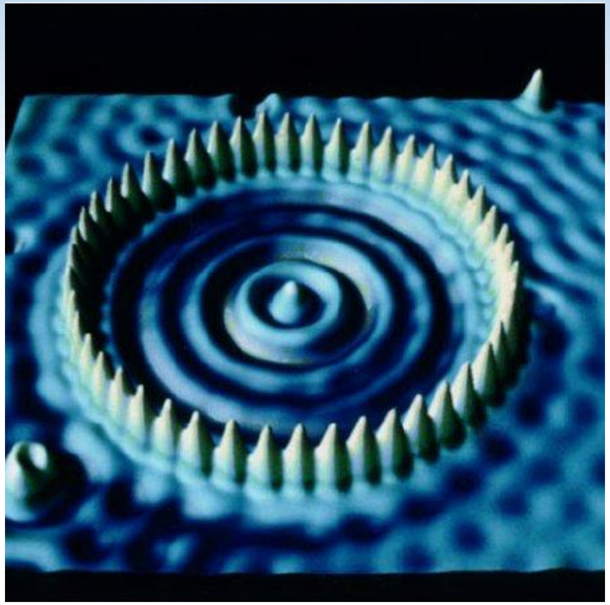
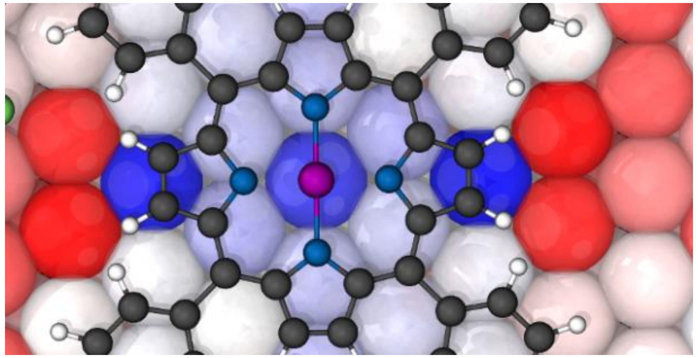


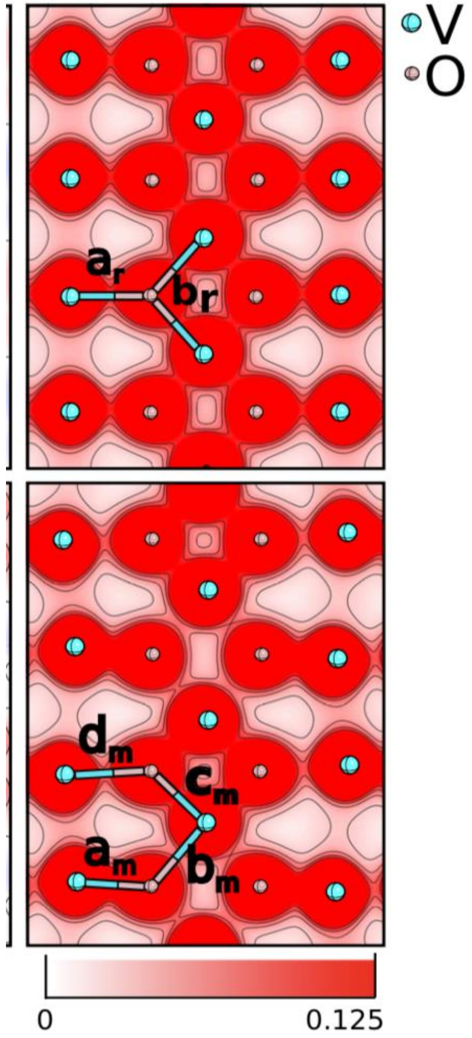
D. Eigler, IBM Research Center, Almaden, CA

Quantum physics

Welcome to PHYS 214!



Phys. Rev. Lett. 105 106601 (2010). Courtesy of H. Kulik



Your comments/questions/jokes

- "I'm excited to learn this semester!"
- "what did the cell phone send to the cell tower... nothing, it just waved"
- "so phil, is it?" 
- Some (all?) of you are having trouble accessing secured course material
  - Should be fixed soon; we will "unsecure" most material in the meantime. You can click the links as usual.
- How will the course be graded?
  - Checkpoints, lecture attendance, homework, labs, discussions, exams. Refer to course website.

Course directors and contact info

Course director
Prof. Naomi Makins
(makins@illinois.edu)
(217) 721-3793
prefer text over email!

Lecturer
Siddharth Mansingh
(sm38@illinois.edu)

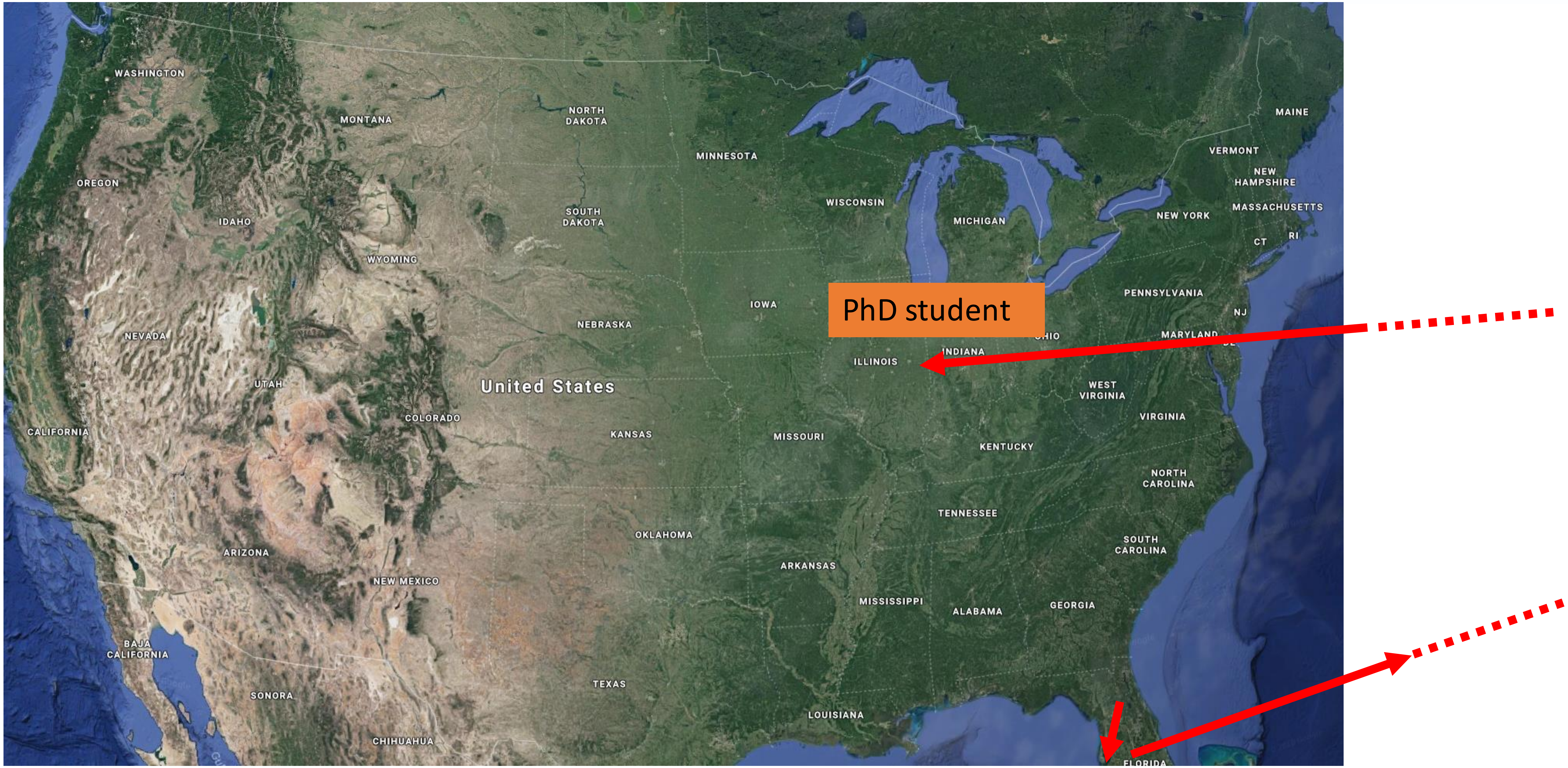
Lecturer
Nick Abboud
(nka2@illinois.edu)

Undergrad office (registration, etc): undergrad@physics.illinois.edu

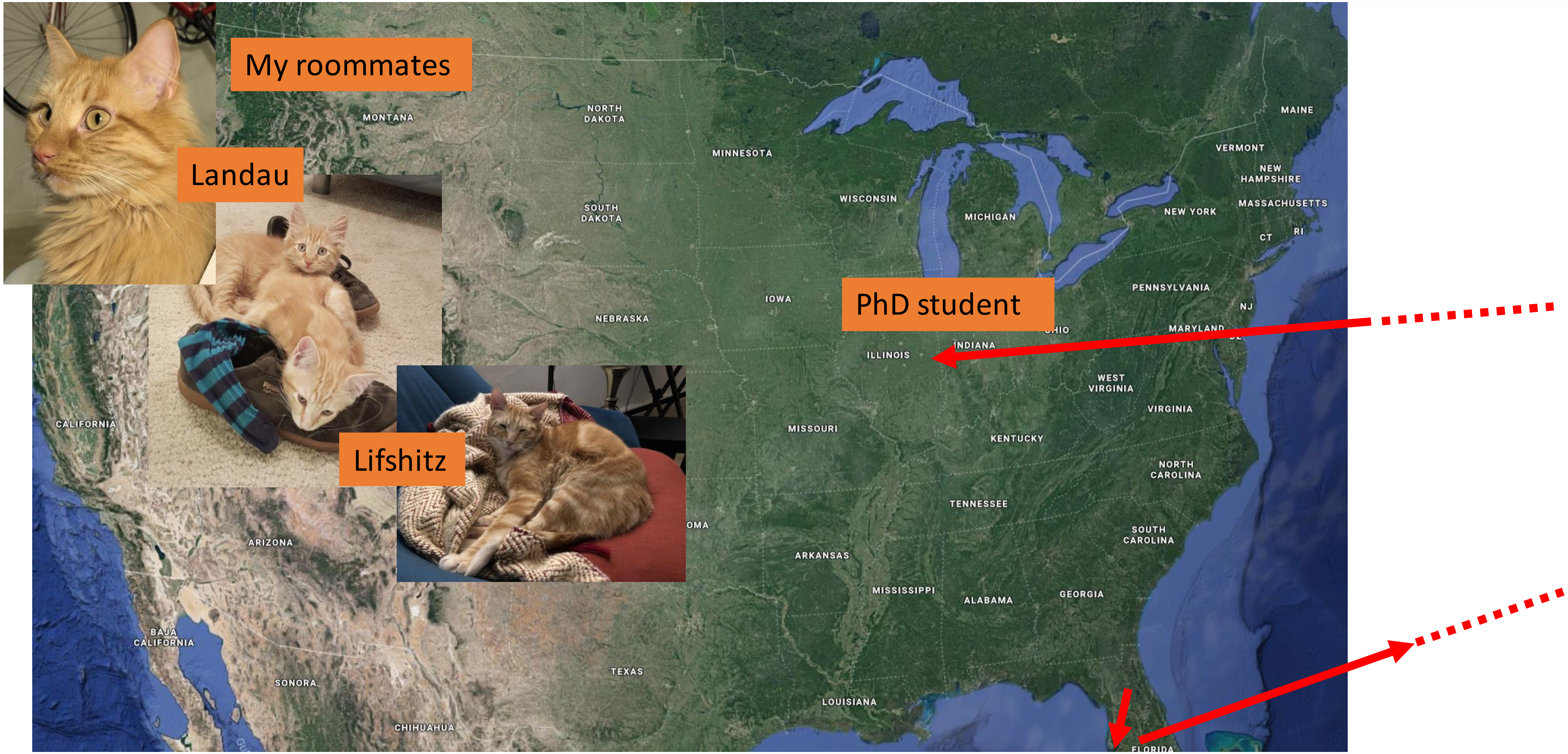
Only email us from your @illinois.edu account.

Please use CampusWire for most questions/requests. That way they get routed to the right person.

About me (Nick)

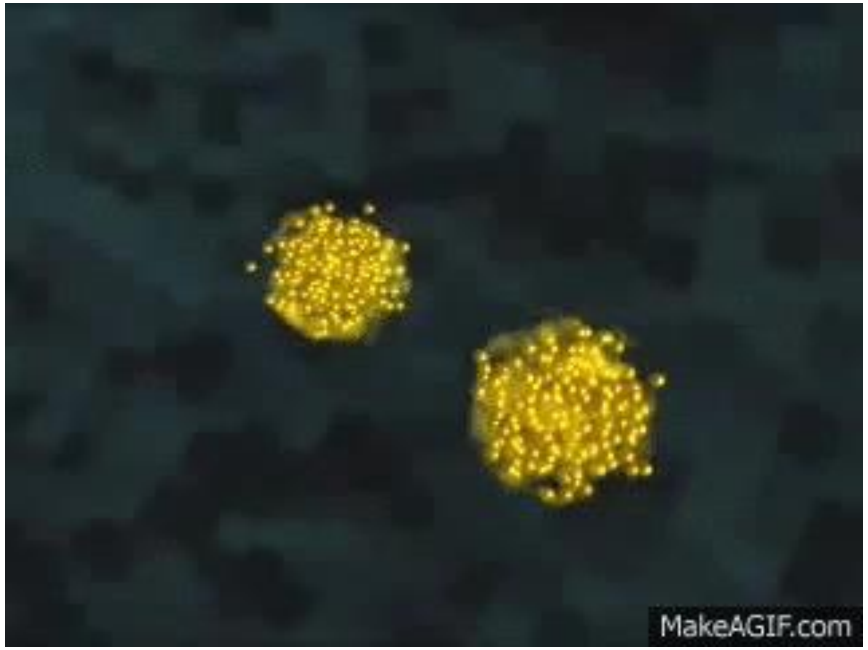


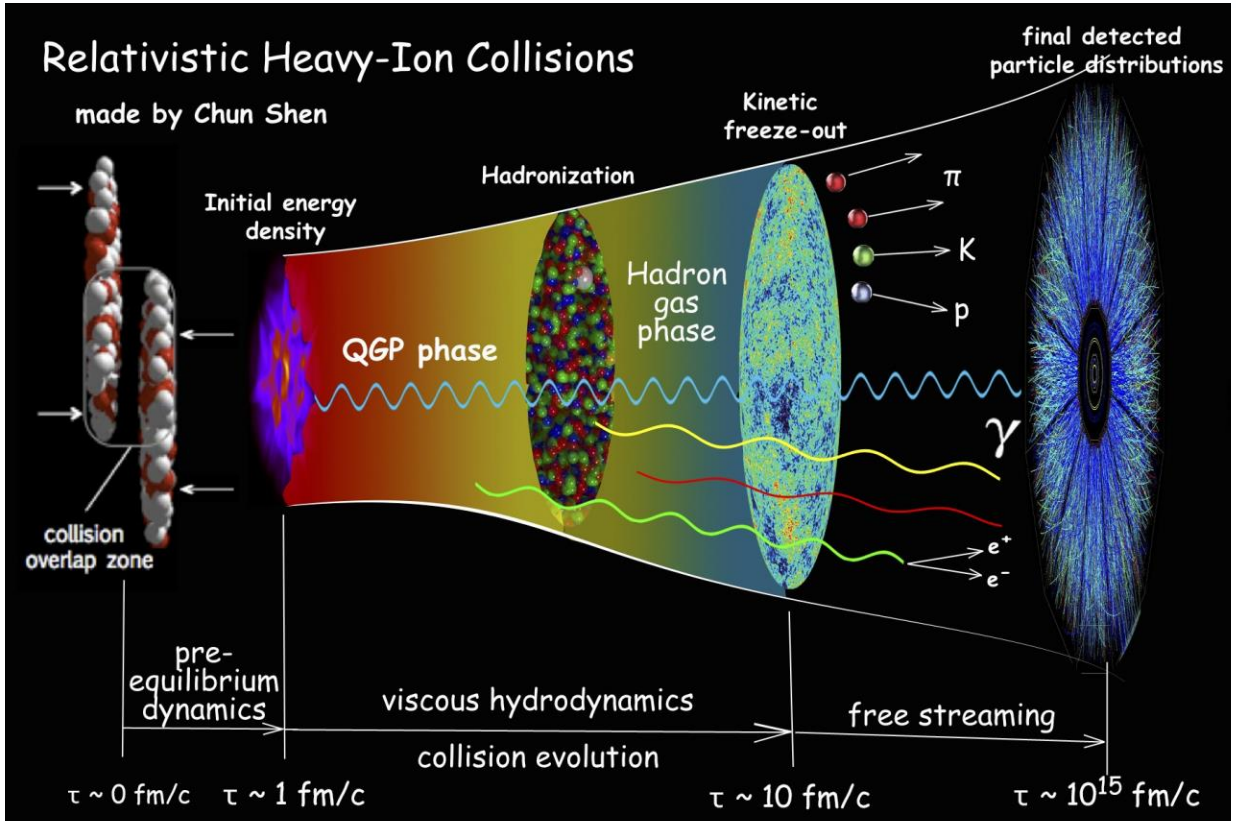
About me (Nick)



About me (Nick) - research - nuclear theory

A heavy-ion collision (e.g. Gold Nucleus + Gold Nucleus)





Some questions

- What phases of matter does the strong nuclear force give rise to?
- How to formulate and extend relativistic hydrodynamics?
- How to simulate neutron star mergers -> gravitational waves?

About you

1. What's your major?

a) MatSE
b) Physics
c) ECE or CS
d) Chemistry or Chem. Eng.
e) Other

roughly uniform distribution!

About you

2. Cats or dogs?

a) Cats
b) Dogs
c) Don’t like pets
d) Both!
e) Other

Class rules

- Put cell phones away
- Close laptops (tablets OK for notetaking)
- Save conversation for Q&A portions of lecture
- If you’re sick, stay home and get better!
  - Excused absence request form

Class structure

Refer to course schedule page for all due dates and links.

1. **Prelecture**: read notes before each lecture (course schedule)
2. **Checkpoint**: short, due 8:00am before each lecture (smartPhysics)
3. **Lecture**: take notes, discuss clicker questions in small groups (here)
4. **Homework**: work in study groups, use Campuswire, attend office hours (smartPhysics)
5. **Discussion**: work on problems in small groups (1047 Sidney Lu Mech. Eng. Bldg.)
6. **Lab**: experience the physics, complete lab worksheets (64 Loomis)
7. **Exams**: 2 midterms and 1 final (CBTF; see course schedule; use the online scheduler in advance!)

Read the course website

http://courses.physics.illinois.edu/phys214

If you have a question, check the website!

Excused absences, grading, schedule, etc..

Getting help

Homework and physics questions: Office hours and Campuswire
(Please don’t post solutions!)

Excuses/absences: Check the webpage. Most things are explained there.

Logistical/policy questions: Course website, then Campuswire

DRES exam accommodations: CBTF, see "exam info" page on course website

Recommended textbook: *University Physics with Modern Physics* by Young & Freedman (12th Edition, 2008)

Campuswire

Post any questions you have there; we will help as soon as we can!

Please do not:

- Ask or share direct solutions
- Be unconstructive

Please do:

- Help your fellow students (crafting an explanation is great practice!)
- Read answers to other people's questions (maybe they'll help you!)
- Let us know if something is wrong

Emergency response

Run > Hide > Fight

Emergencies can happen anywhere and at any time. It is important that we take a minute to prepare for a situation in which our safety or even our lives could depend on our ability to react quickly. When we're faced with almost any kind of emergency – like severe weather or if someone is trying to hurt you – we have three options: Run, hide or fight.

Run

Leaving the area quickly is the best option if it is safe to do so.

- Take time now to learn the different ways to leave your building.
- Leave personal items behind.
- Assist those who need help, but consider whether doing so puts yourself at risk.
- Alert authorities of the emergency when it is safe to do so.

Hide

When you can't or don't want to run, take shelter indoors.

- Take time now to learn different ways to seek shelter in your building.
- If severe weather is imminent, go to the nearest indoor storm refuge area.
- If someone is trying to hurt you and you can't evacuate, get to a place where you can't be seen, lock or barricade your area if possible, silence your phone, don't make any noise and don't come out until you receive an Illini-Alert indicating it is safe to do so.

Fight

As a last resort, you may need to fight to increase your chances of survival.

- Think about what kind of common items are in your area which you can use to defend yourself.
- Team up with others to fight if the situation allows.
- Mentally prepare yourself – you may be in a fight for your life.

Please be aware of people with disabilities who may need additional assistance in emergency situations.

Other resources

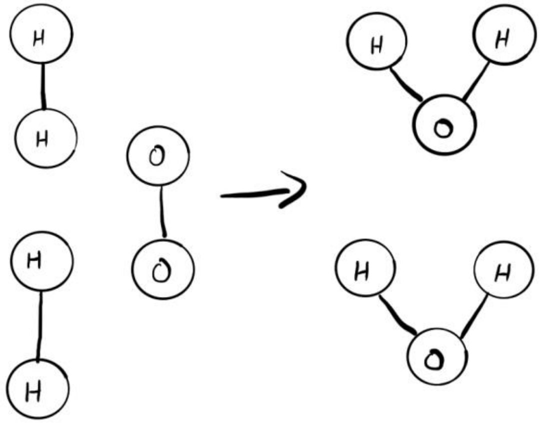
- **police.illinois.edu/safe** for more information on how to prepare for emergencies, including how to run, hide or fight and building floor plans that can show you safe areas.
- **emergency.illinois.edu** to sign up for Illini-Alert text messages.
- **Follow the University of Illinois Police Department** on Twitter and Facebook to get regular updates about campus safety.

Quantum mechanics

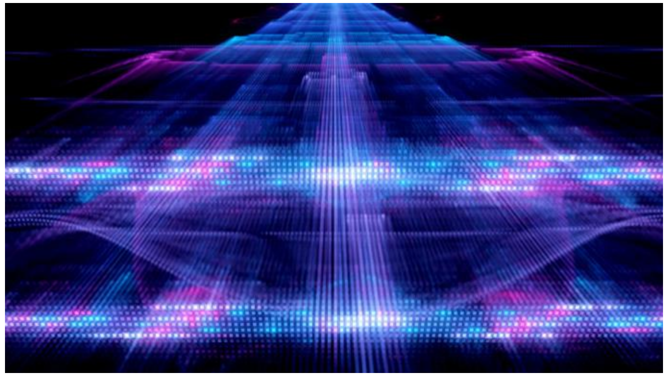
Quantum mechanics is the toolset used to describe many things.

Electronics

Chemistry



New ways of computing
and transmitting information



Course plan

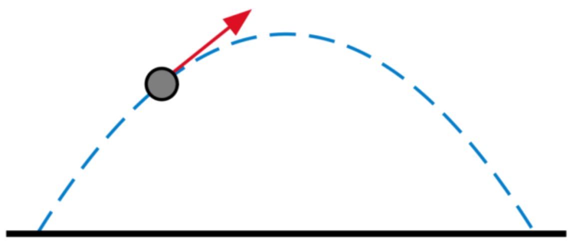
1. Classical waves
   - Interference and diffraction
   - Applications: interferometers, spectroscopy, diffraction-limited optics
2. Wave-particle duality
   - Light waves arrive in lumps (photons), and lumps of matter (electrons, protons, etc.) have wave-like properties
   - Complex numbers, wavefunction, position/momentum measurement, double-slit experiment, photoelectric effect
3. Quantum states
   - States with definite properties and time-dependent states
   - Schrödinger equation
   - Particle in a box, quantum harmonic oscillator, energy levels, transitions
4. Atoms, molecules and solids
   - The hydrogen atom, building the periodic table from quantum mechanics
   - Electrons in solids: band structure
   - Two-state systems: light polarization, quantum mechanical spin
5. Applications

Classical vs quantum

Soon we'll learn that $|\Psi(x,t)|^2 \Delta x$ is the probability of finding the particle between x and $x+\Delta x$ at time t aka "Born Rule"

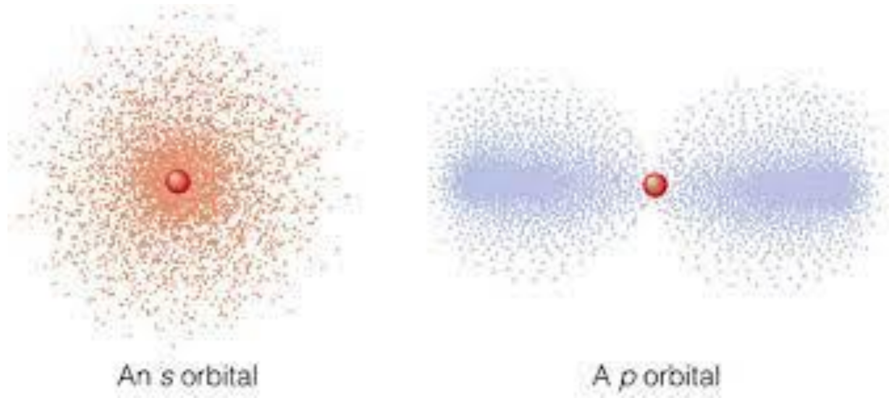
Classical mechanics
$x(t)$

Objects have *definite* position as a function of time



Quantum mechanics
$\Psi(x,t)$

At a given time, we can only describe the *probability* of observing a particle at a certain position



The wavefunction obeys an equation called the Schrödinger equation

$\Psi(x,t)$ is called the particle's *wavefunction* describes the position of the particle *probabilistically*

It obeys the Schrödinger equation

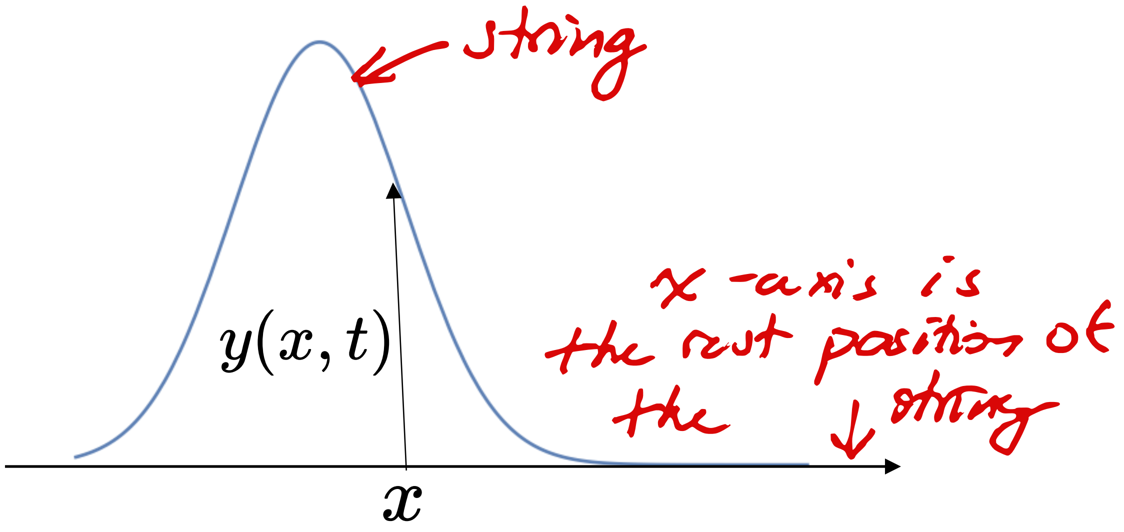
$$i\hbar\frac{\partial\Psi(x,t)}{\partial t} = -\frac{1}{2m}\frac{\partial^2\Psi(x,t)}{\partial x^2} + V(x)\Psi(x,t)$$

(don't need to understand this yet!)

which looks *kind of* like the wave equation describing waves on a string

$$\frac{\partial^2 y(x,t)}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 y(x,t)}{\partial t^2}$$

so we need to understand these "classical waves" first

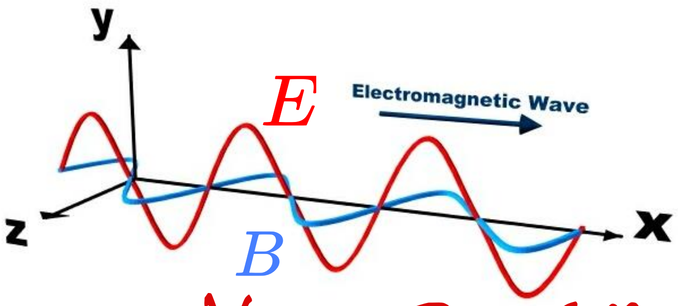


There are many examples of classical waves

$$y(x,t) = \ldots$$

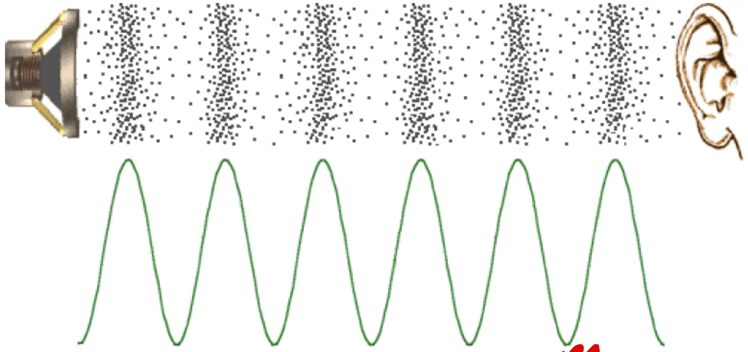
height of a water wave

a component of electric or magnetic field in a radio wave



$V = c = 3 \times 10^8$ m/s

pressure in a sound wave

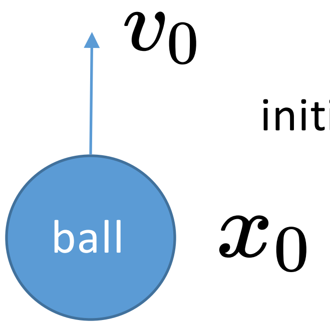


$V \approx 300$ m/s

All satisfy the wave equation (at least approximately)

$$\frac{\partial^2 y(x,t)}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 y(x,t)}{\partial t^2}$$

The *equations of motion* tell us what happens



initial position and velocity

$x(t)$ = height of ball above ground

Equation of motion: $$m\frac{d^2x}{dt^2} = -mg$$

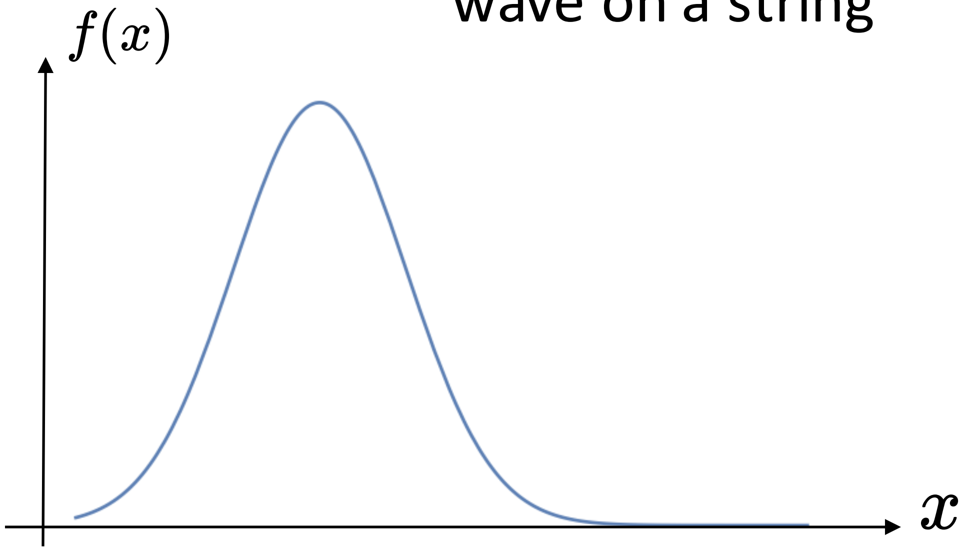
Guess solution: $$x(t) = x_0 + v_0 t - \frac{1}{2}gt^2$$

Check if equation of motion is satisfied

Check if initial conditions are satisfied

If so, x(t) describes what the ball actually does!

wave on a string



Equation of motion: $$\frac{\partial^2 y(x,t)}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 y(x,t)}{\partial t^2}$$

Guess a solution: $$y(x,t) = f(x - vt)$$

Check if equation of motion is satisfied

If so, y(x, t) describes a possible motion of the string!

We are avoiding getting into the details of initial conditions for a string...

$$x(t) = x_0 + v_0 t - \frac{1}{2} g t^2$$

$$x(0) = x_0 \checkmark$$

$$\frac{dx}{dt} = v_0 - gt \Rightarrow \frac{dx}{dt}(0) = v_0 \checkmark$$

$$\frac{d^2x}{dt^2} = -g \Rightarrow m\frac{d^2x}{dt^2} = -mg$$

so both the equation of motion and the initial conditions are satisfied

$\Rightarrow x(t)$ is what the ball does

$$y(x,t) = f(x - vt)$$

$$\frac{\partial y}{\partial x} = f'(x - vt) \qquad \frac{\partial^2 y}{\partial x^2} = f''(x - vt)$$

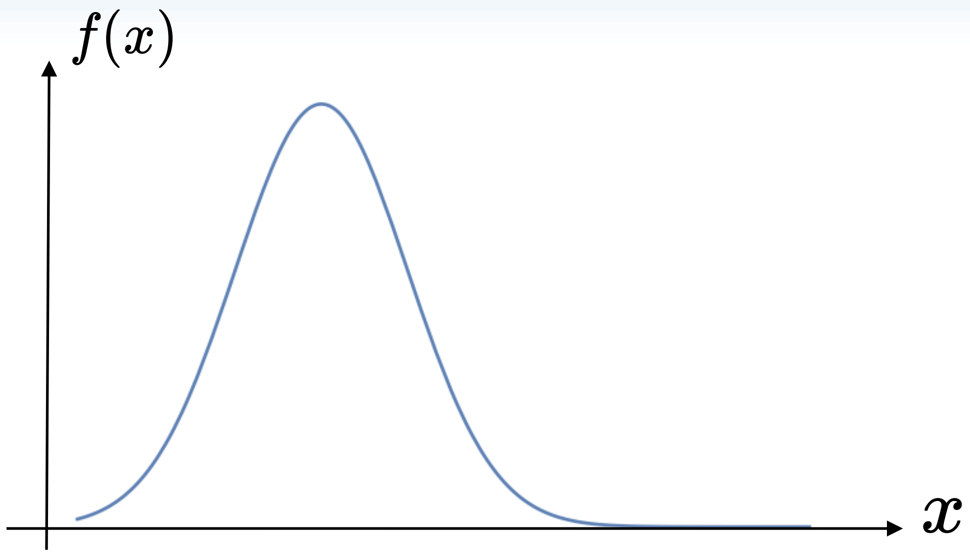
$$\frac{\partial y}{\partial t} = -v f'(x - vt)$$

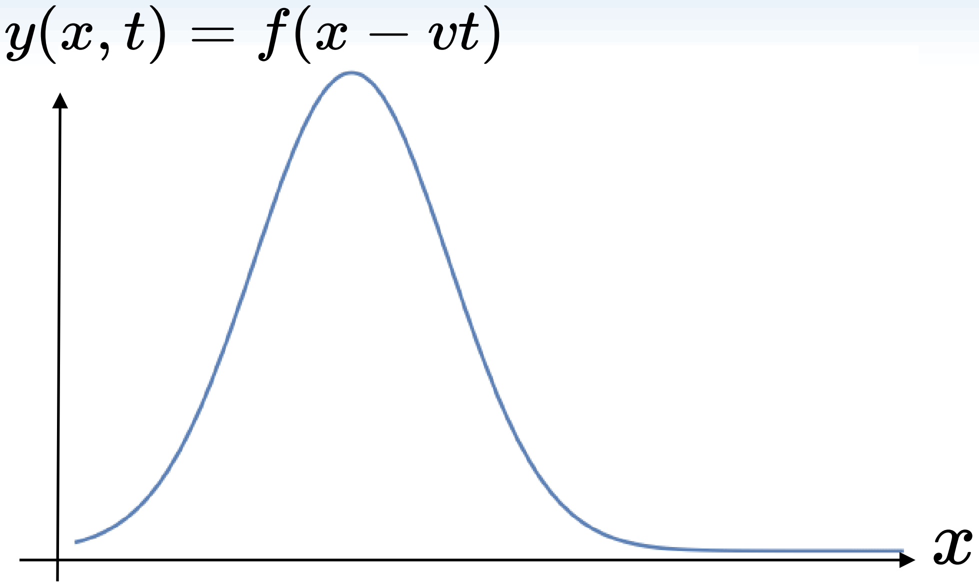
$$\frac{\partial^2 y}{\partial t^2} = +v^2 f''(x - vt)$$

$$\Rightarrow \frac{\partial^2 y}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 y}{\partial t^2}$$

no matter what f looks like, $y(x,t) = f(x - vt)$ is a valid solution to the equation of motion.

We have discovered *travelling wave* solutions



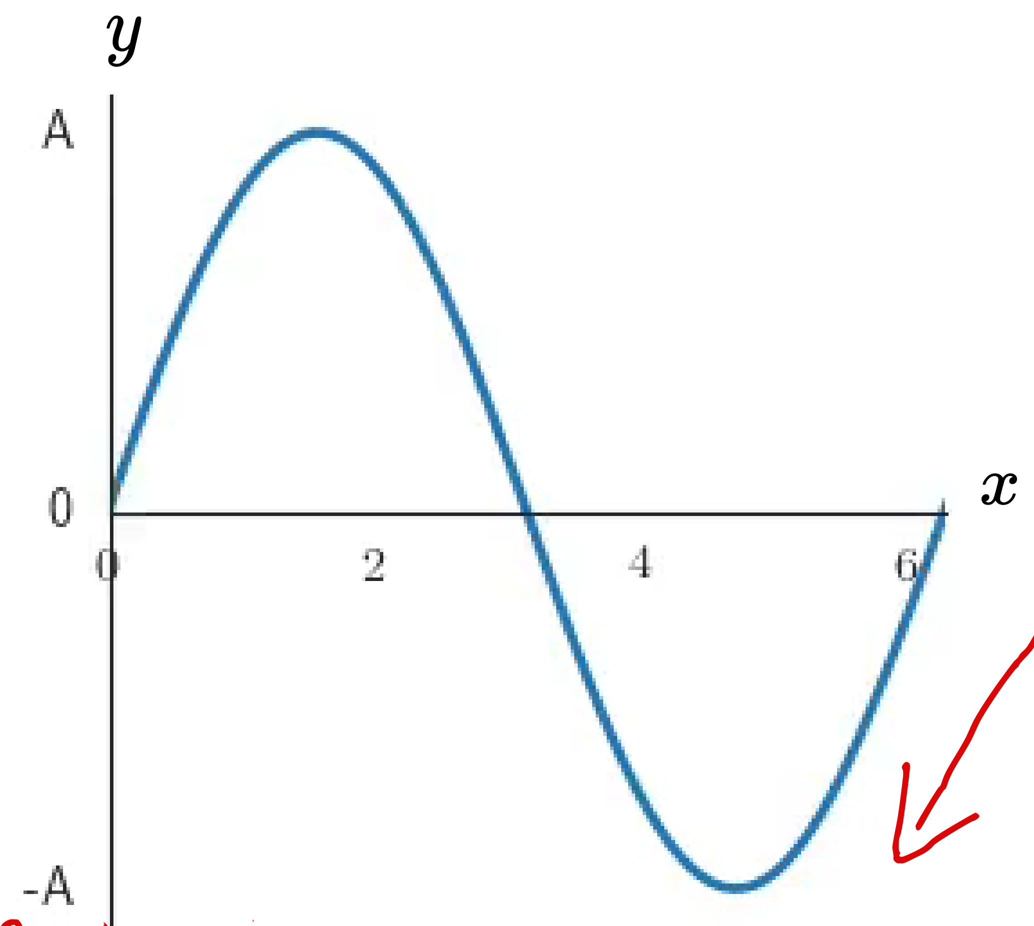


Note:

- $f(x)$ can be any shape
- We haven't talked about the *ends* of the string...
- The *wave speed* v is a property of the string (depends on tension, mass density) and is same for all waves

you can make a wave like this with a taut rope. just jiggle the left end of the rope for a moment.

Harmonic travelling waves are travelling waves with a sinusoidal shape



Here is a harmonic travelling wave:

$$y(x,t) = A\cos(kx - \omega t + \phi)$$

This wave is moving...

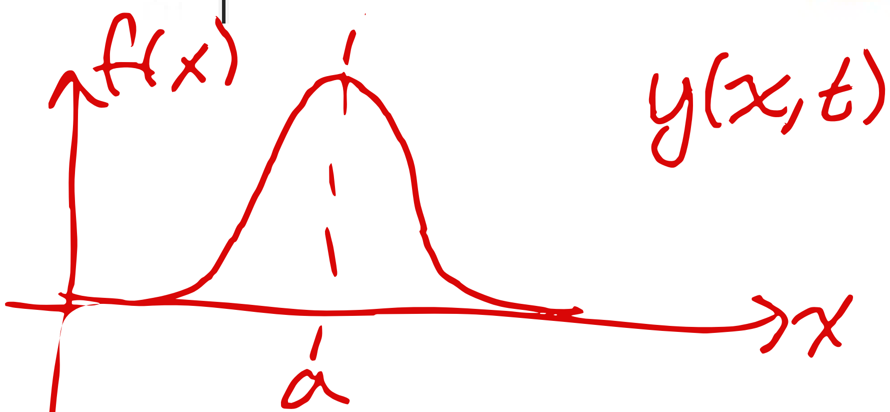
A) rightward
B) leftward
C) squidward

k and ω must be related to the wave speed v for this to be a true solution. How are they related?

A) $k\omega = v$
B) $\omega = v$
C) $\frac{\omega}{k} = v$

can check the units.

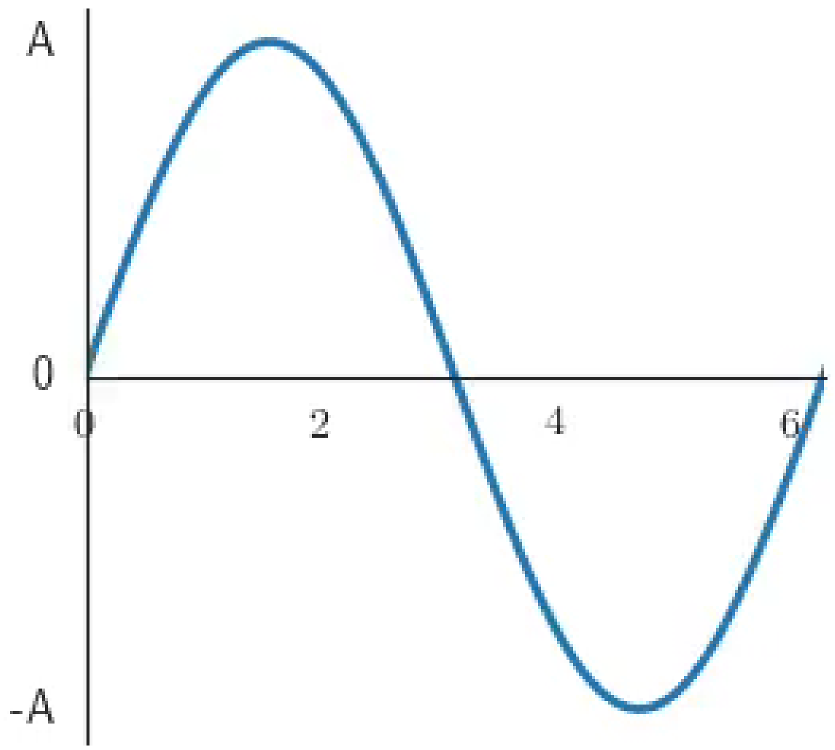
also, $kx - \omega t = k(x - (\frac{\omega}{k})t)$ ← v



$y(x,t) = f(x - vt)$

to track the location of the maximum, set inside of f to a. $x - vt = a \Rightarrow x = vt + a$.
$\Rightarrow$ x increases.

The anatomy of a harmonic travelling wave



$$y(x,t) = A\cos(kx - \omega t + \phi)$$

amplitude (A), wavenumber (k), angular frequency (ω), phase offset (ϕ)

$$\frac{\omega}{k} = v$$

wave speed (v)

$$\lambda = \frac{2\pi}{k}$$

wavelength (λ)

period

$$T = \frac{2\pi}{\omega}$$

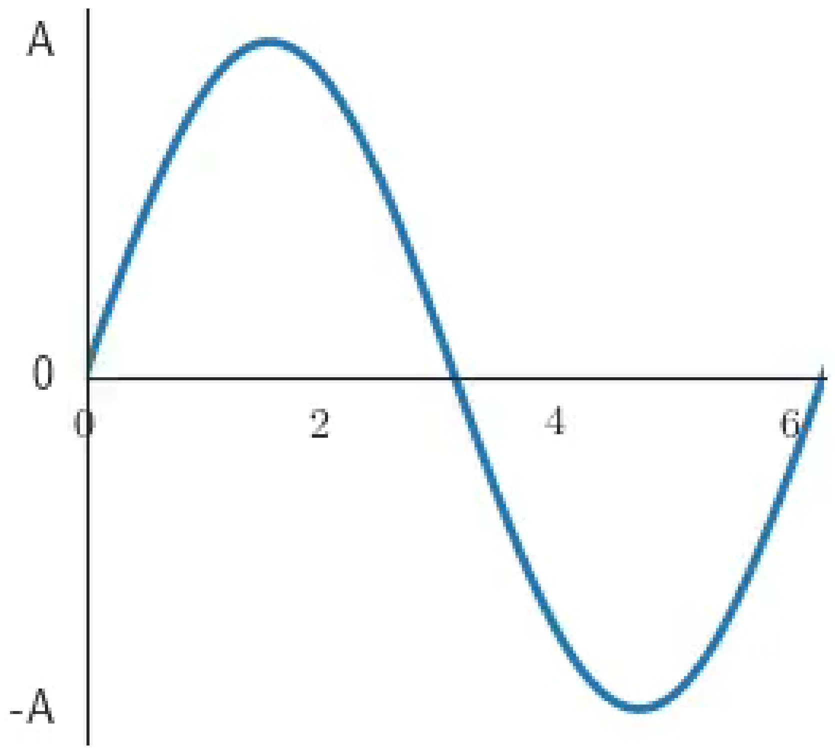
$$v = \lambda f$$

$$\omega = 2\pi f$$

frequency (f)

To understand and talk about harmonic waves, it is important to know what these quantities mean and why they are related in these ways

The anatomy of a harmonic travelling wave



$$y(x,t) = A\cos(kx - \omega t + \phi)$$

amplitude (A)

wavenumber (k)

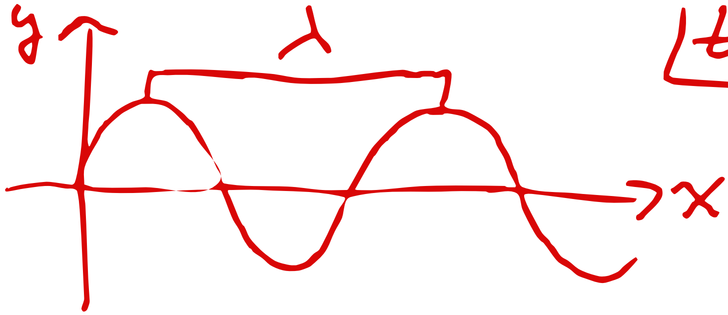
angular frequency (ω)

phase offset (ϕ)

To understand and talk about harmonic waves, it is important to know what these quantities mean and why they are related in these ways

1. Why is $\frac{2\pi}{k}$ equal to the wavelength λ ?
2. Why is $\frac{2\pi}{\omega}$ equal to the period T?
3. Why $v = \lambda f$?
4. What does the phase offset ϕ signify?

1.



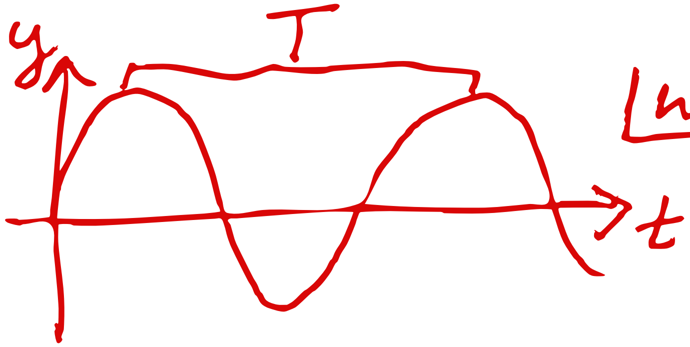
t = 0 snapshot

$$y(x,0) = A\cos(kx+\phi)$$

$$k\lambda = 2\pi$$ [λ is the Δx that makes the inside of cos advance by 2π]

$$\Rightarrow \boxed{\lambda = \frac{2\pi}{k}}$$

2.



wave observed from x = 0

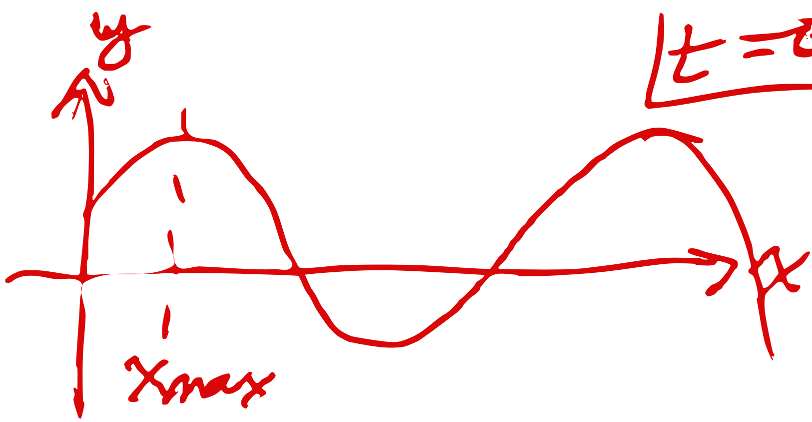
$$y(0,t) = A\cos(-\omega t+\phi) = A\cos(\omega t - \phi)$$

$$\omega T = 2\pi$$ [same argument]

$$\Rightarrow \boxed{T = \frac{2\pi}{\omega}}$$

3. $v = \dfrac{\omega}{k} = \dfrac{2\pi/T}{2\pi/\lambda} = \dfrac{\lambda}{T} = \lambda f$ (using $f = \frac{1}{T}$)

4.



t = 0

$$y(x,0) = A\cos(\underbrace{kx+\phi}_{=0 \text{ when } x = x_{max}})$$

$$kx_{max} + \phi = 0 \Rightarrow x_{max} = -\frac{\phi}{k}$$

so changing ϕ <u>shifts</u> the wave

Waves transport energy

$$\text{Average Intensity} = \frac{\text{Average Power}}{\text{Area}} = \frac{(\text{Energy Transmitted})/(\text{Time})}{\text{Area}}$$

Sunlight intensity is about 1000 W/m^2 at Earth's surface. What is the approximate energy absorbed by a *perfect* 30 cm x 30 cm solar panel during a 10 second interval?

A) 10 J
B) 100 J
C) 1,000 J
D) 10,000 J

Area $= (30 cm)^2$
$= (0.3)^2 m^2$
$\approx \frac{1}{10} m^2$

$\Rightarrow 1000 W = \frac{\text{energy}/(10 \text{ sec})}{(\frac{1}{10} m^2)}$

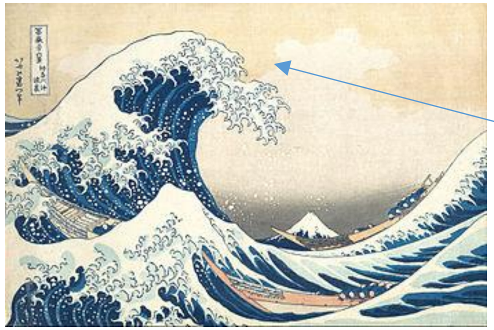
$\Rightarrow$ energy $= 1000$ J

Wave amplitude

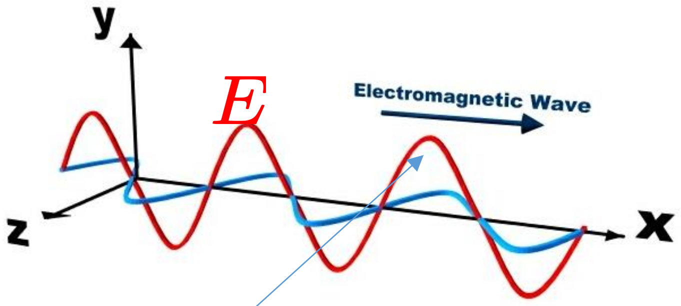
$$y(x,t) = \ldots$$

- height of water in a water wave
- component of E-field in a light wave
- pressure in a pressure wave
- generally called the *displacement* at x and t

The *amplitude* of a wave is the largest (peak) value of the displacement.



$$A = 3\ \mathrm{m}$$

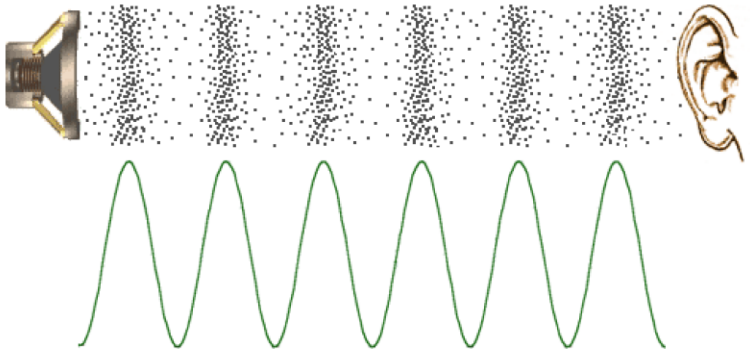


$$A = 700\ \mathrm{N/C}$$

sunlight @ Earth's surface

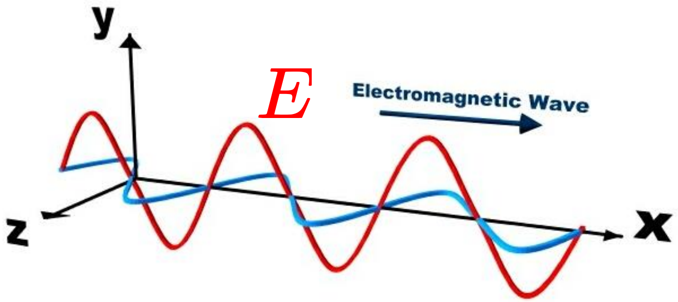
$$A = 1\ \mathrm{Pa} = 1\ \mathrm{N/m^2}$$

loud traffic



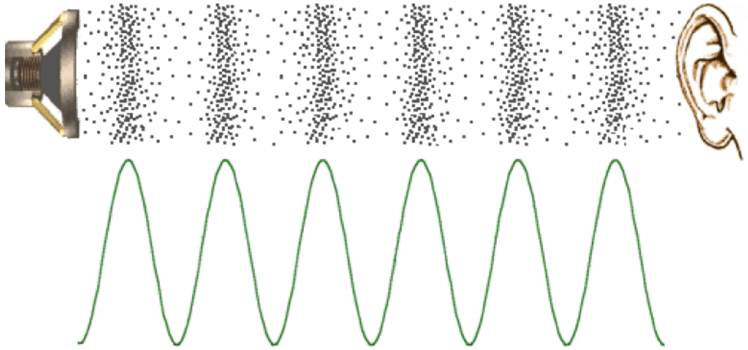
Intensity is proportional to the square of the amplitude

$I \propto (\text{max height})^2$
approximately



$I \propto (\text{max E})^2$
exactly (in vacuum)

$$I = \frac{E_{\text{max}}^2}{2\mu_0 c}$$

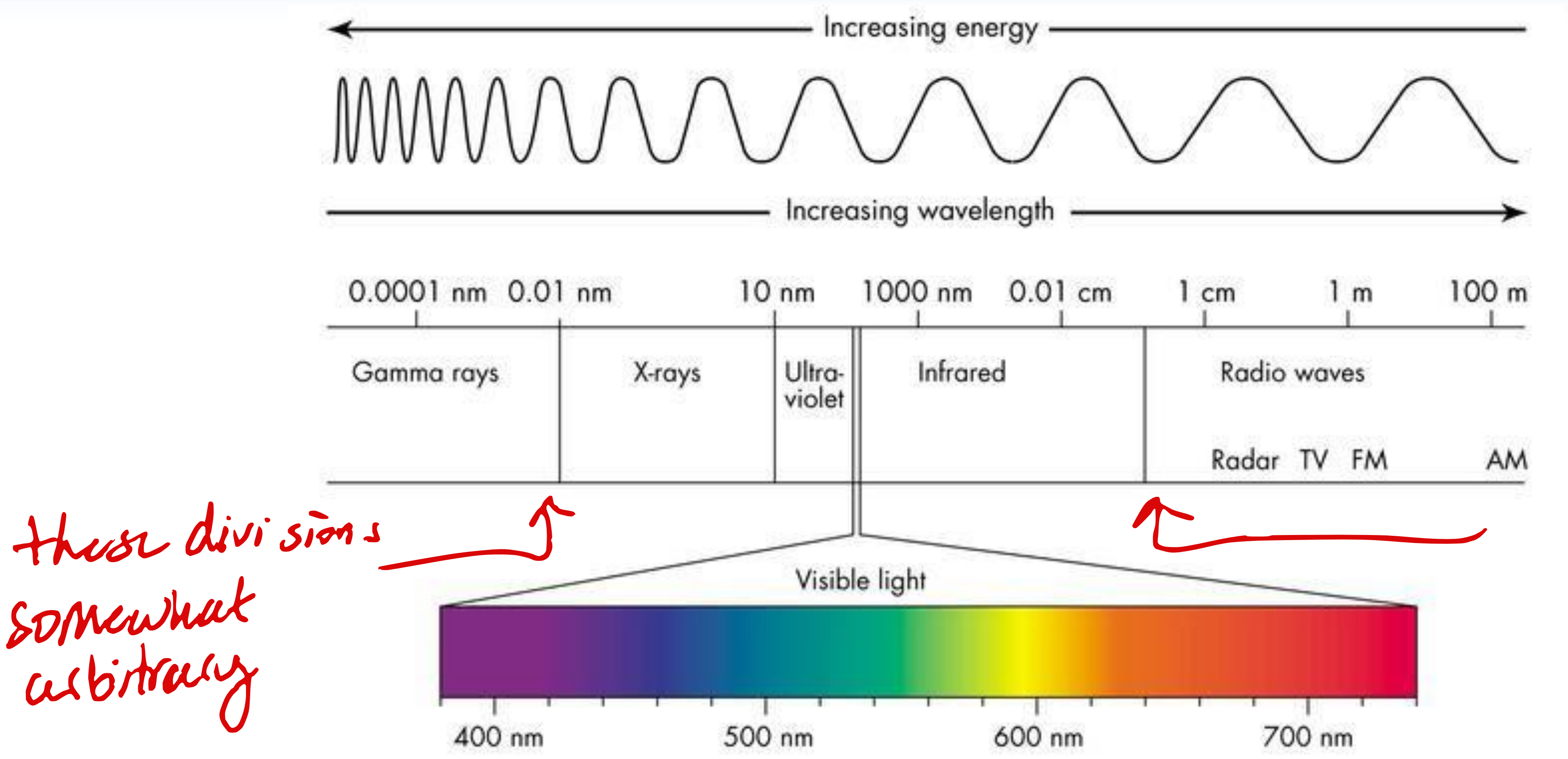


$I \propto (\text{max pressure})^2$
approximately

For many types of waves, the intensity is (at least approximately) proportional to the amplitude

$$I \propto A^2$$

Spectrum of electromagnetic radiation



Summary: harmonic waves

Amplitude	A
Average Intensity	$I \propto \frac{A^2}{2}$
Frequency	f
Wavelength	λ
Phase offset	ϕ
Period	$T = \frac{1}{f}$
Velocity	$v = \lambda f$
Wave number	$k = \frac{2\pi}{\lambda}$
Angular frequency	$\omega = 2\pi f$

Which quantity most closely corresponds to how loud a sound is?

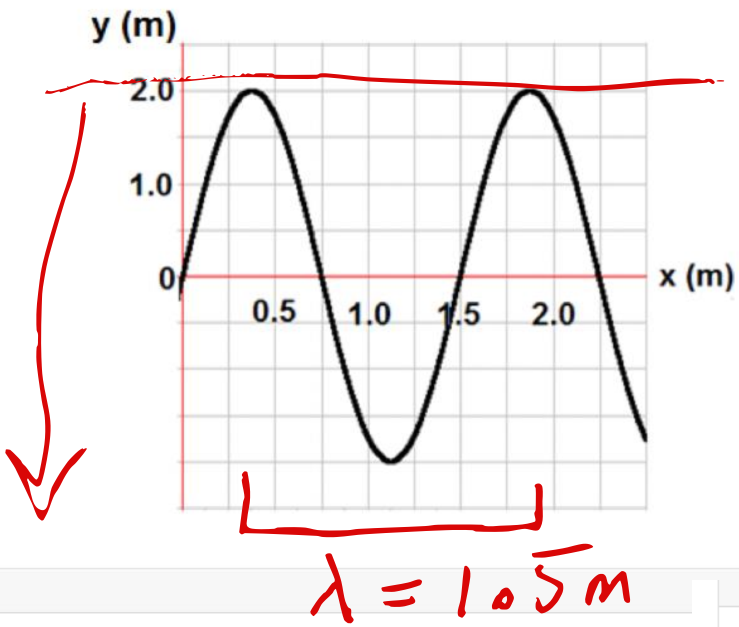
A) Amplitude
B) Intensity
C) Frequency
D) Wavelength
E) Wave speed

→ usually measured on a log scale (decibels)

since human perception of sound is approx. logarithmic.

Sample problem

A wave at a particular instant in time is shown in the figure below:



What is the amplitude of oscillations of this wave at this instant?

- (a) 1.5 m
- (b) 2.0 m
- (c) 0.0 m
- (d) 1.0 m
- (e) 0.5 m

What is the speed of the wave if the frequency of oscillation is 12.0 Hz?

- (a) 18.0 m/s
- (b) 0.00 m/s
- (c) 9.00 m/s
- (d) 12.0 m/s
- (e) 24.0 m/s

$v = \lambda f$

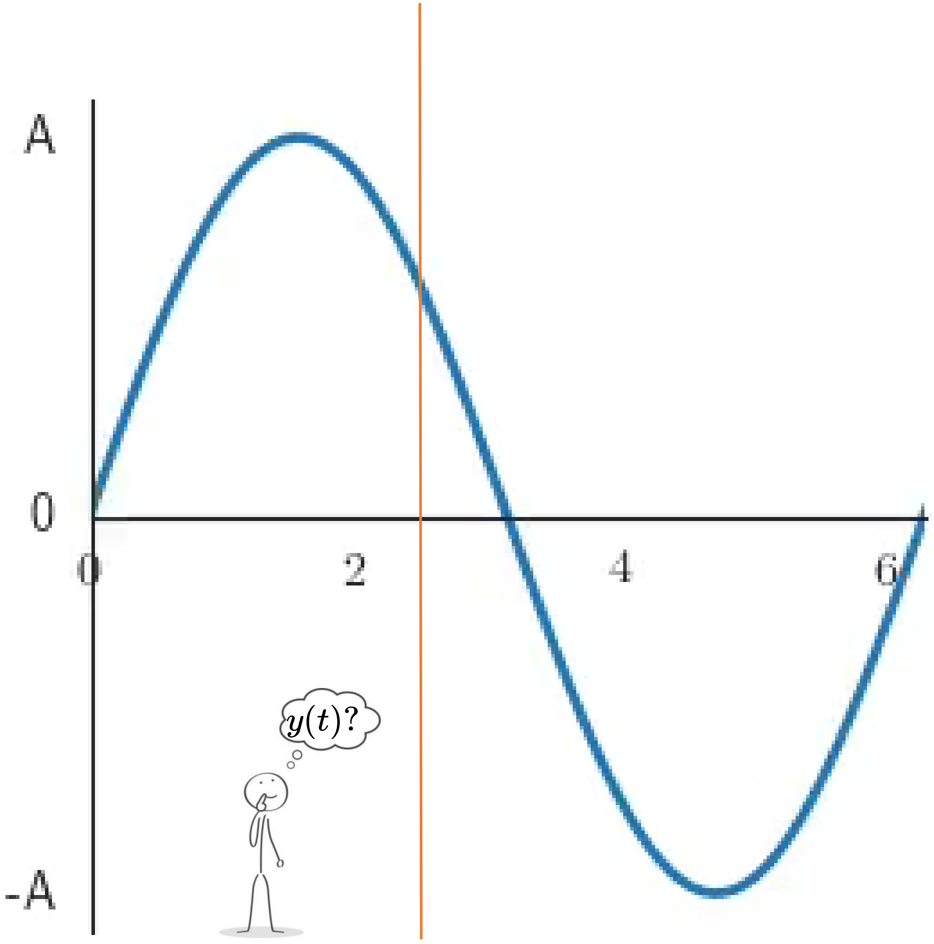
$= (1.5\,m)(12\,Hz)$

$= \frac{3}{2} \times 12\ \frac{m}{s}$

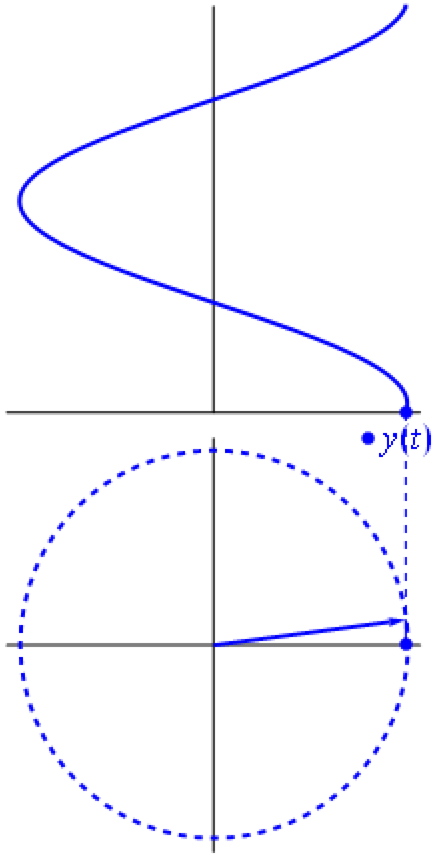
$= 18\ \frac{m}{s}$

No calculator needed!

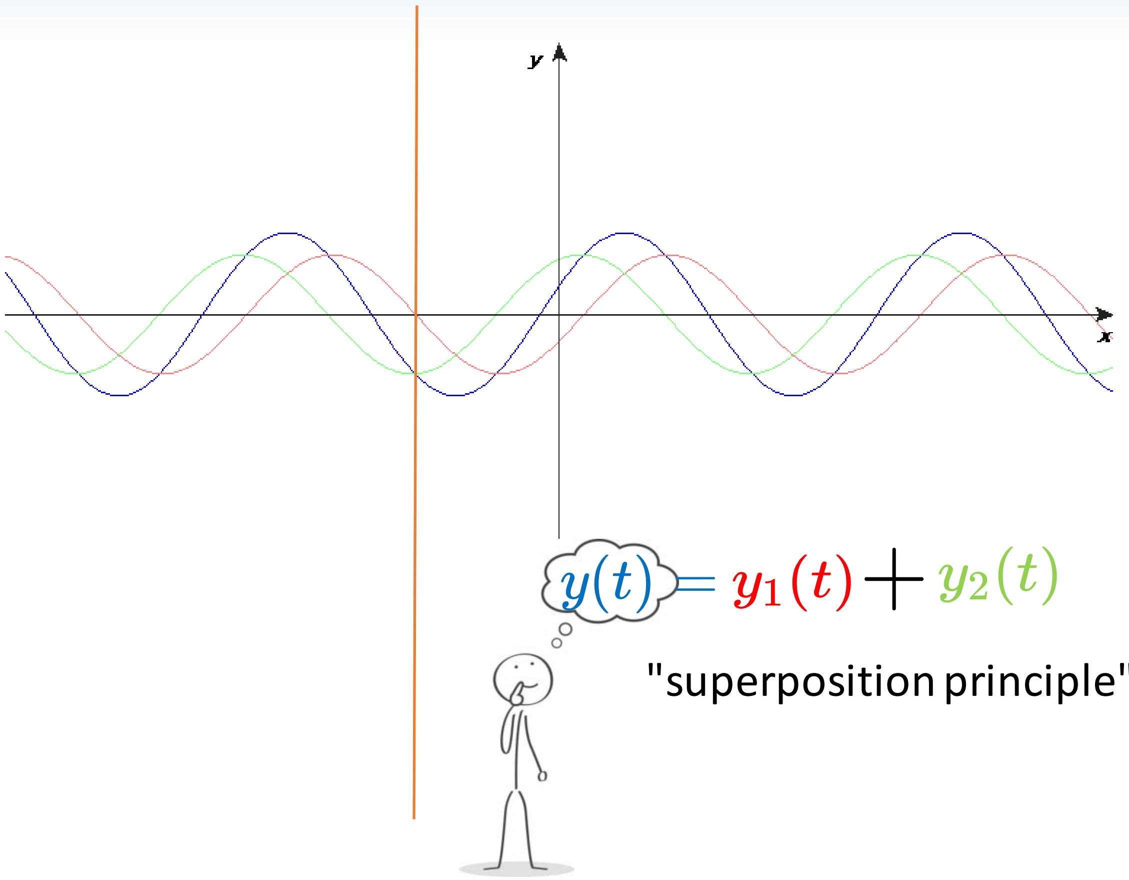
Phasors are a graphical tool for representing and adding harmonically oscillating quantities



$$y(t) = A\cos(\omega t - \varphi)$$



Adding harmonic waves is easier with phasors



$$y(t) = y_1(t) + y_2(t)$$

"superposition principle"

$$y_1(t) = A_1 \cos(\omega t - \varphi_1)$$

$$y_2(t) = A_2 \cos(\omega t - \varphi_2)$$

What is the intensity experienced by the observer?

1. Draw and label the phasor diagram
2. Add the phasors like vectors
3. Find the length of the resultant
4. Take the square: $I \propto A^2$

If $A_1 = A_2$, what is the intensity A^2 at a point where $\varphi_1 = 0$ and $\varphi_2 = \pi/2$

A) $A^2 = 0$

B) $A^2 = 4\,(A_1)^2$

C) $A^2 = 2\,(A_1)^2$