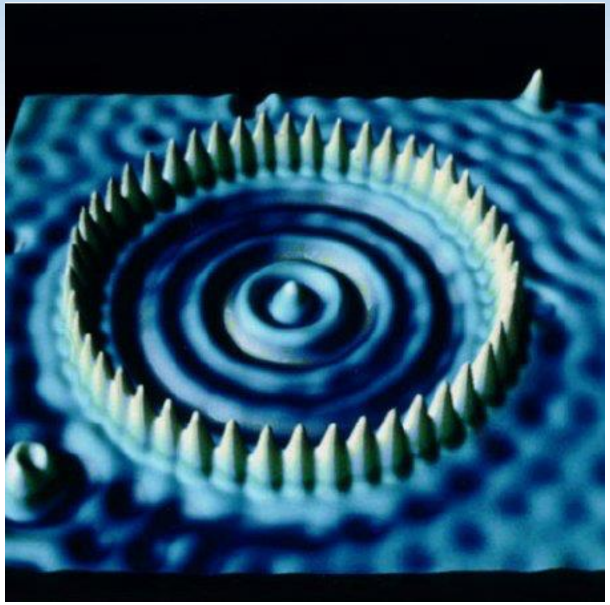
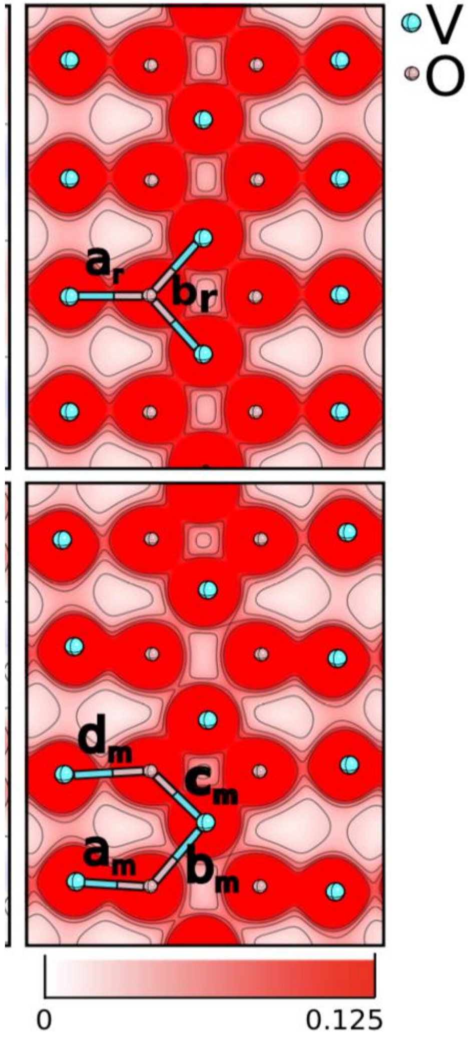
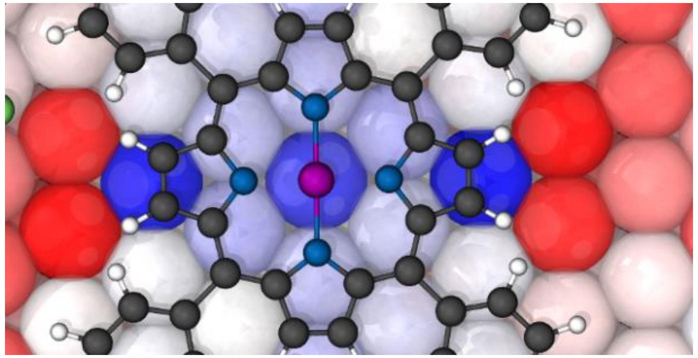


D. Eigler, IBM Research Center, Almaden, CA

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)

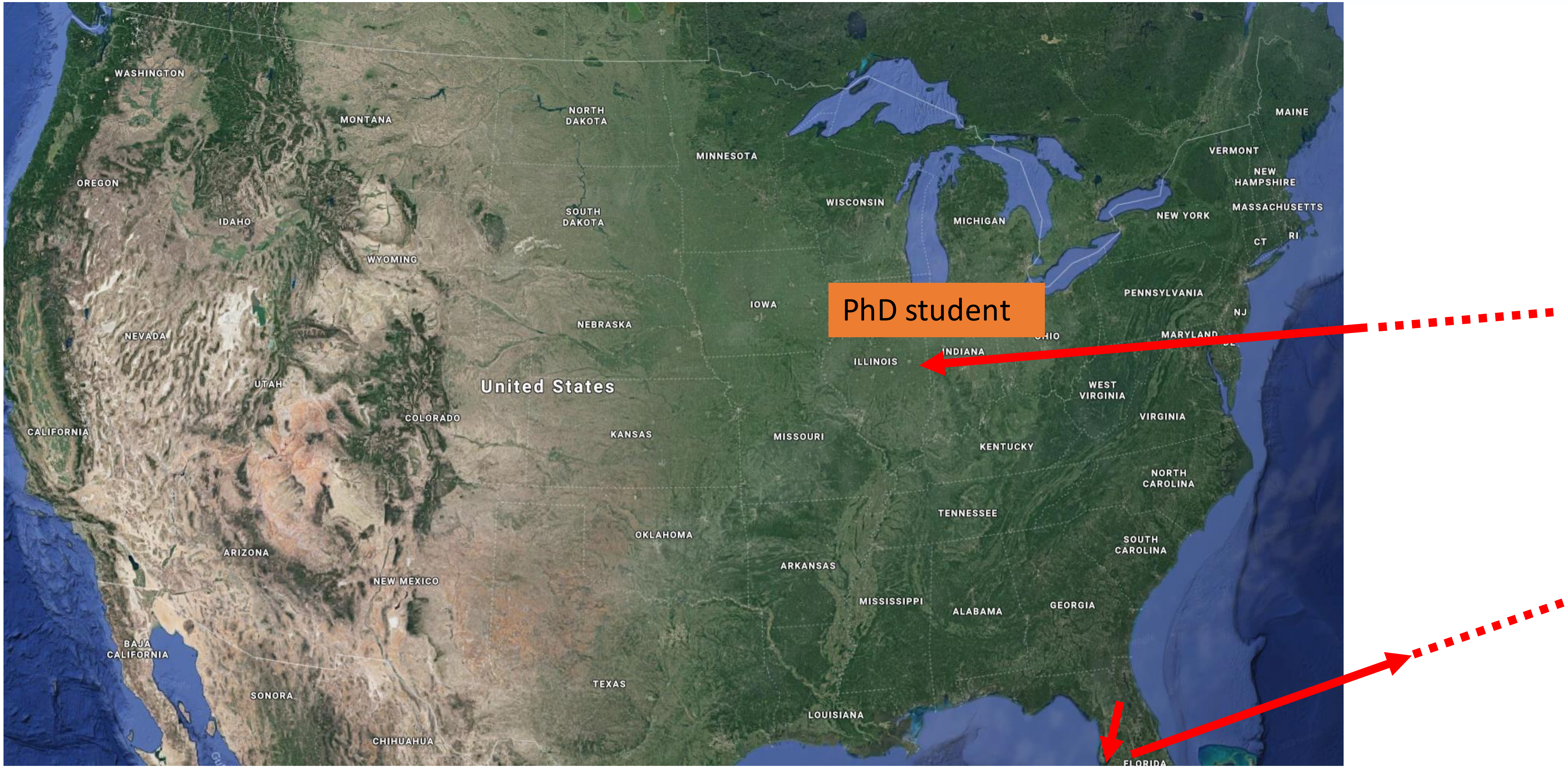
Lecturer
Nick Abboud
(nka2@illinois.edu)

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

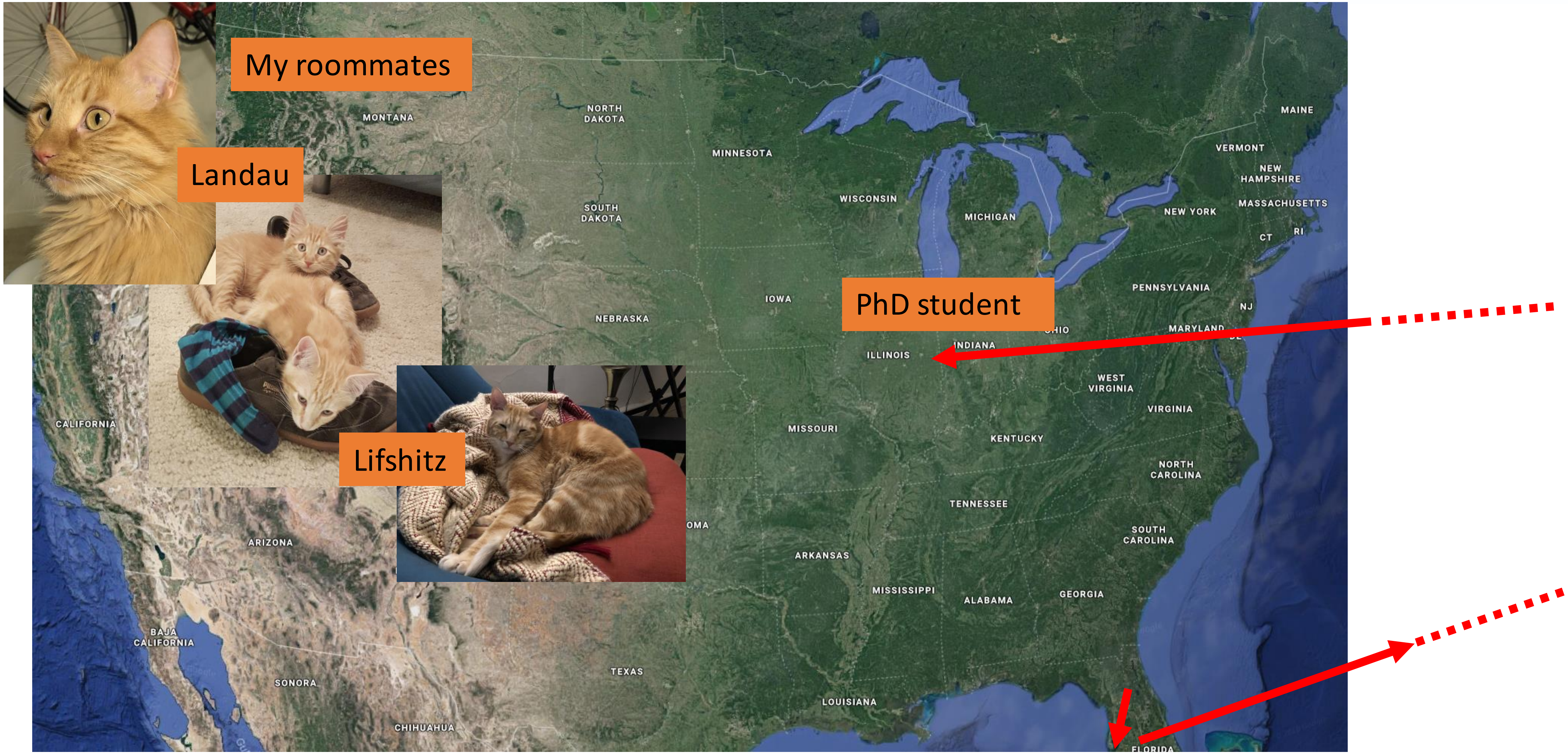
Only email us from your @illinois.edu account.

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

About me (Nick)

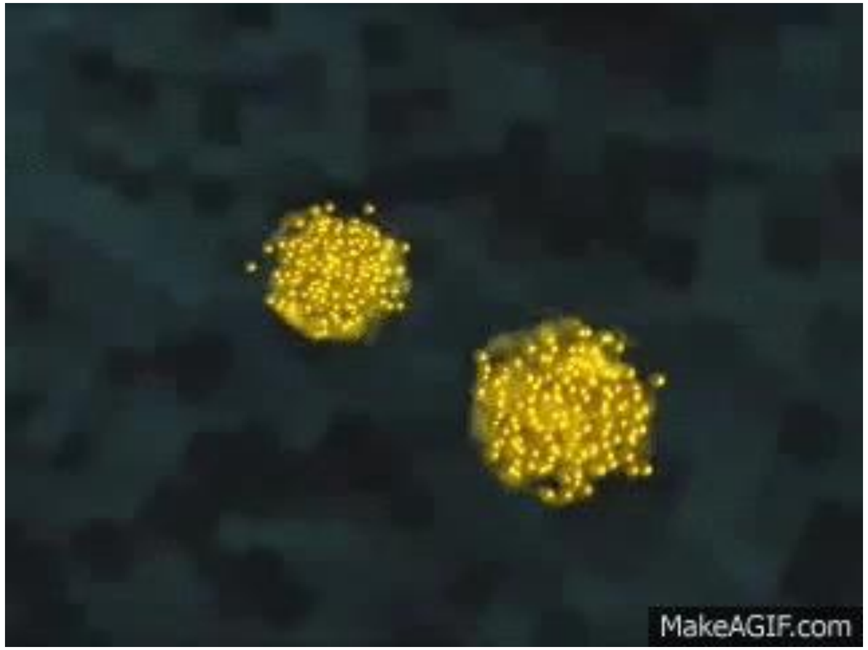


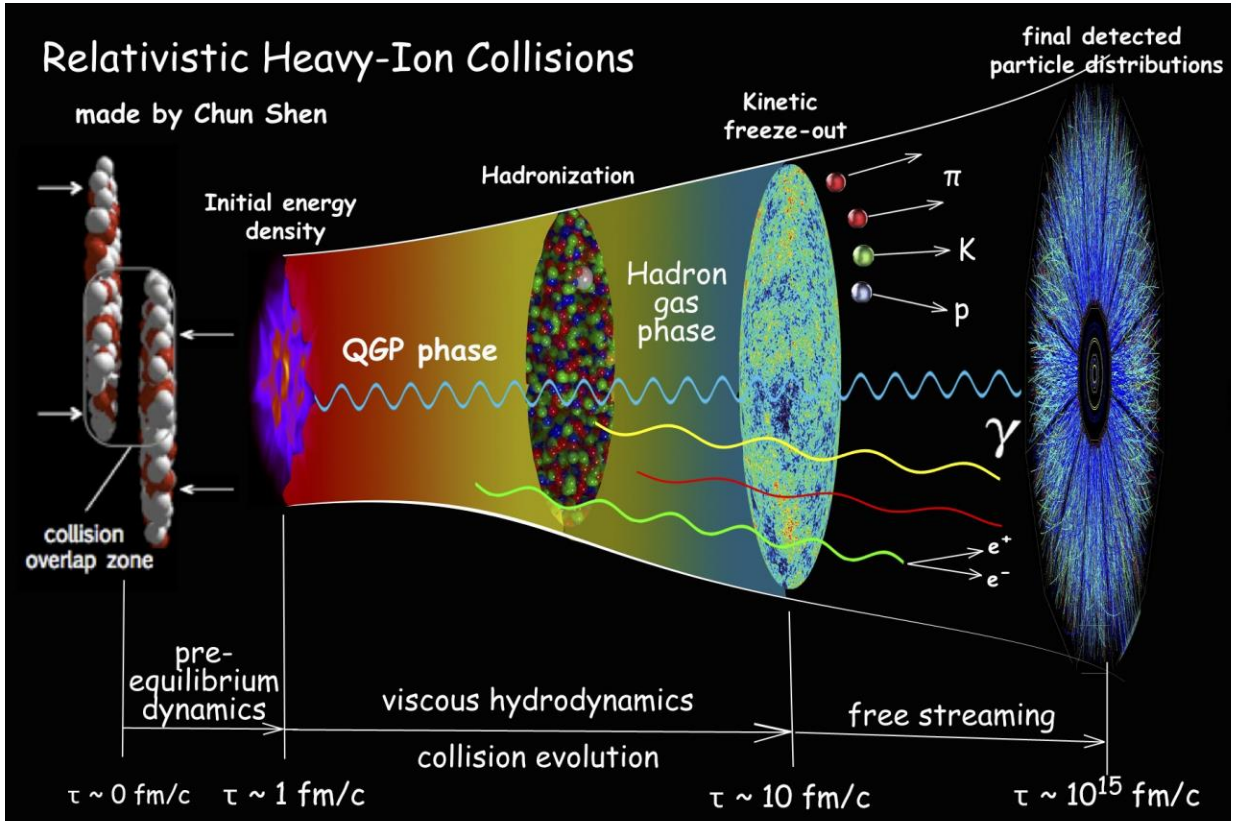
About me (Nick)



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

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 andeat any tim. It is imp or t ant that we take a minute to prepare for a situatio in whi ch our sa fety 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 optios: Run, hide or figh t.

Run

Leaving the area quickly is the best optio if it is sa fe to do so.

- Take tim no w 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 authoritie of the eme r gency when it is safe to do so.

Hide

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

- Take tim no w 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 untily ou receive ag Illini-Alert indicatin it is sa fe to do so.

Fight

As a last resort, you may need to fig t 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 fig t if the situatio al lo ws.
- Mentally prepare yourself – you may be in a fig t for your life.

Please be aware of people with disabilitie who ma y need additioal assi s tance in emergency situatios.

Other resources

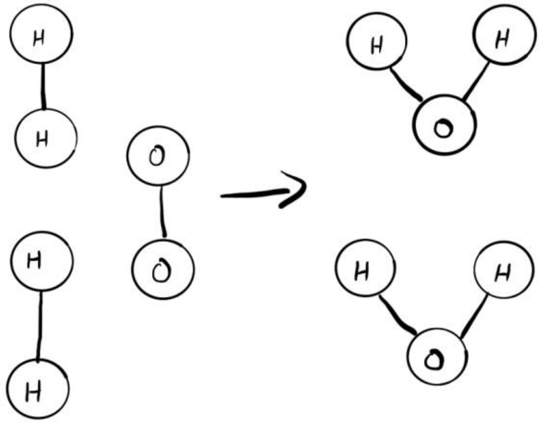
- **police.illinois.edu/safe** for more informatio on ho w to prepare for emergencies, including b how to run, hide or fig t and building flor pl ans tha t can show you safe areas.
- **emergency.illinois.edu** to sign up for Illini-Alert text messages.
- **Follow the University of Illinois Police Department** on Twitter and Facebook to get regular updates about campus safety.

Quantum mechanics

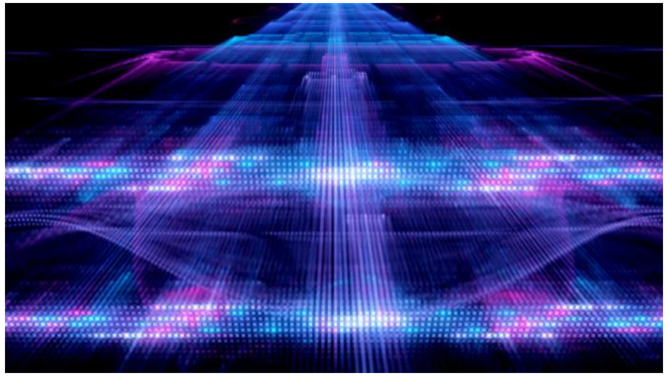
Quantum mechanics is the toolset used to describe many things.

Electronics

Chemistry



New ways of computing
and transmitting information



Course plan

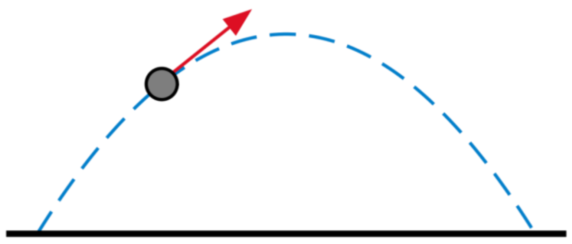
1. Classical waves
    - Interference and diffraction
    - Applications: interferometers, spectroscopy, diffraction-limited optics
2. Wave-particle duality
    - Light waves arrive in lumps (photons), and lumps of matter (electrons, protons, etc.) have wave-like properties
    - Complex numbers, wavefunction, 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

Classical mechanics

$x(t)$

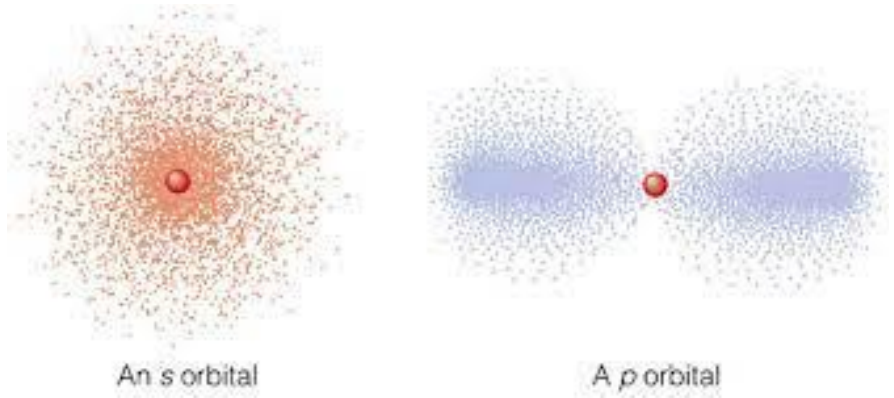
Objects have *definite* position as a function of time



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

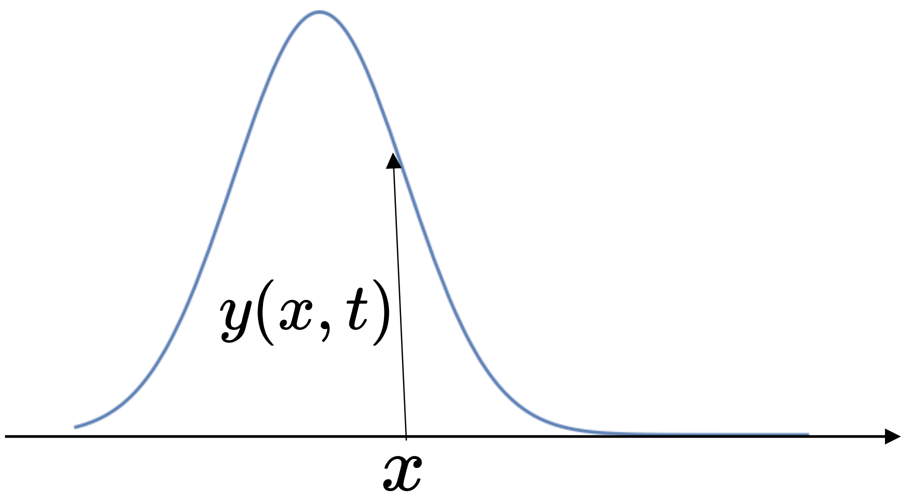
$$i\hbar\frac{\partial\Psi(x,t)}{\partial t} = -\frac{1}{2m}\frac{\partial^2\Psi(x,t)}{\partial x^2} + V(x)\Psi(x,t)$$

(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

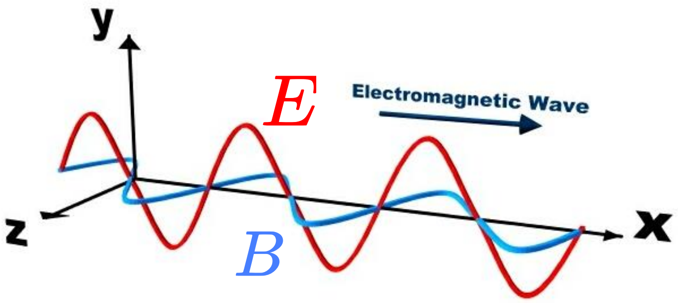


There are many examples of classical waves

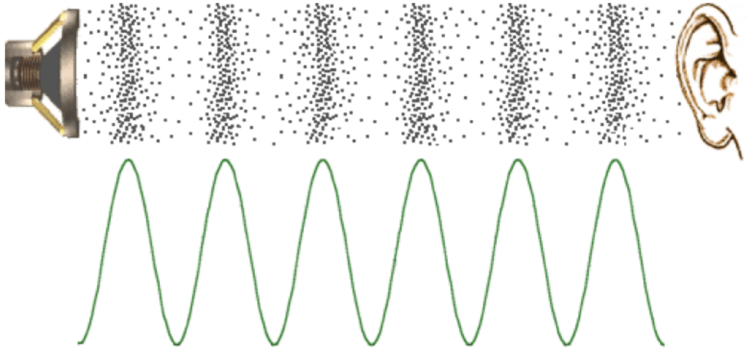
$$y(x,t) = \dots$$

height of a water wave

a component of electric or
magnetic field in a radio wave



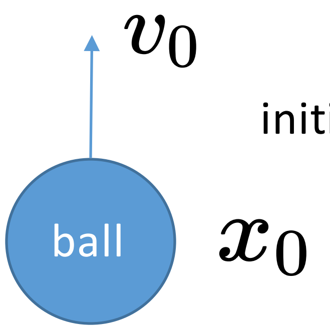
pressure in a sound wave



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

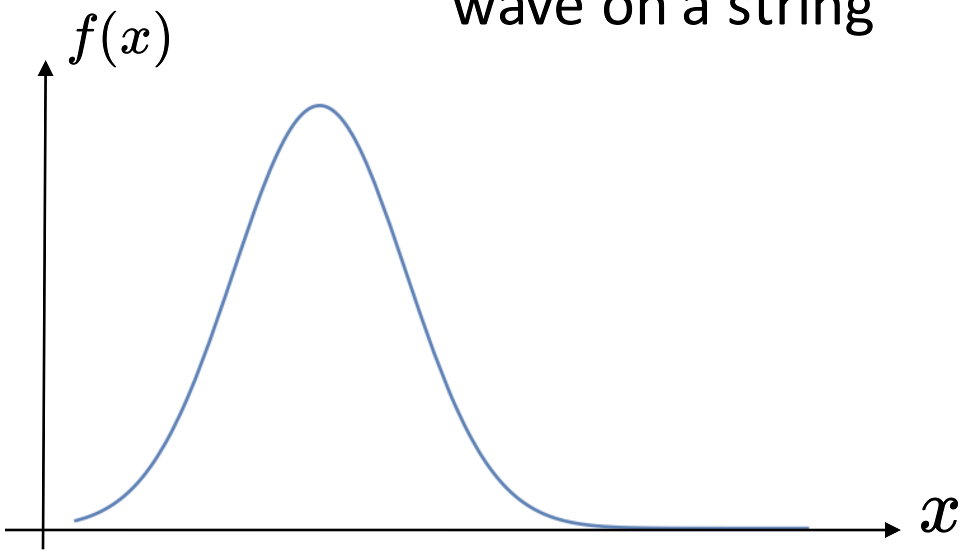
Guess solution: $$x(t) = x_0 + v_0 t - \frac{1}{2}gt^2$$

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

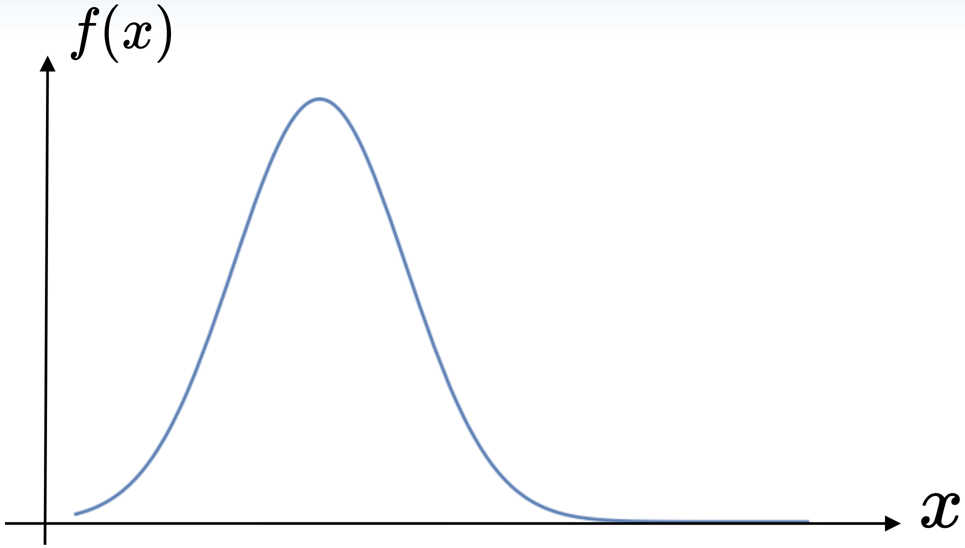
Guess a solution: $$y(x,t) = f(x - vt)$$

Check if equation of motion is satisfied

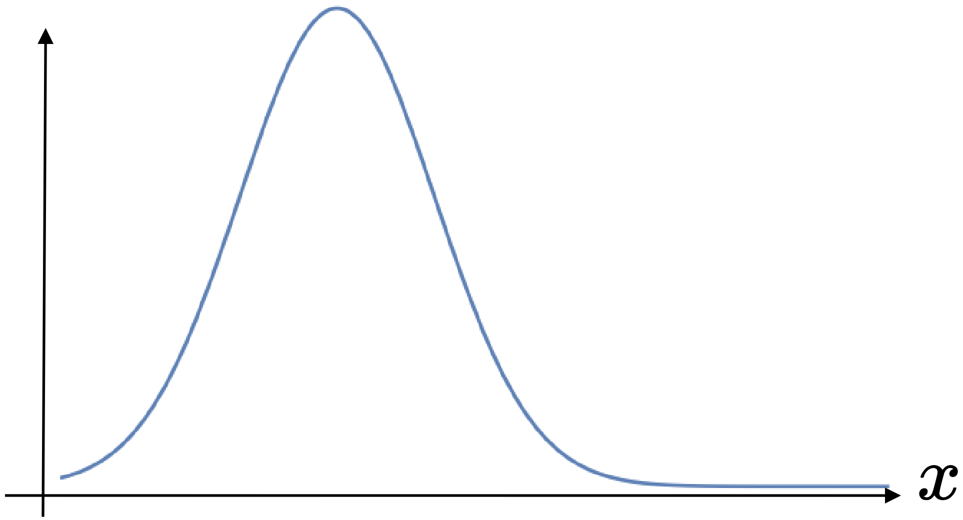
If so, y(x, t) describes a possible motion of the string!

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

We have discovered *travelling wave* solutions



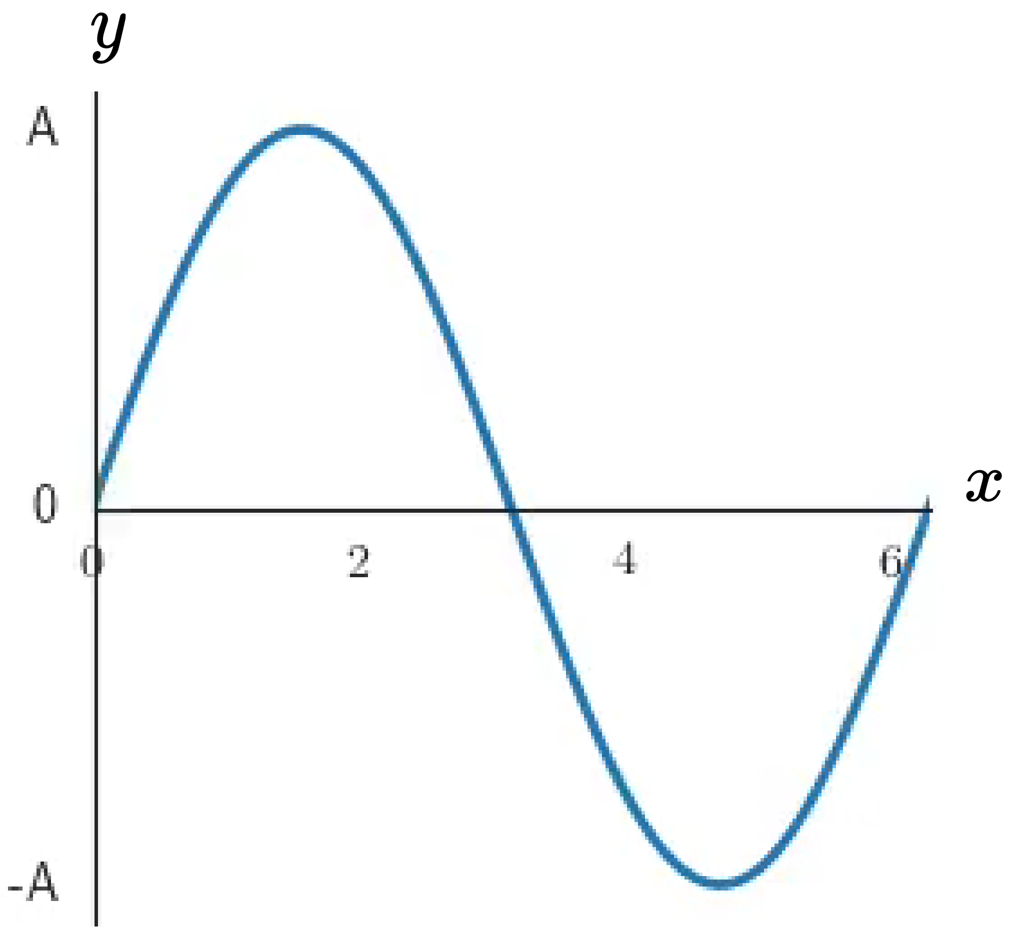
$$y(x,t) = f(x - vt)$$



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

Harmonic travelling waves are travelling waves with a sinusoidal shape



Here is a harmonic travelling wave:

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

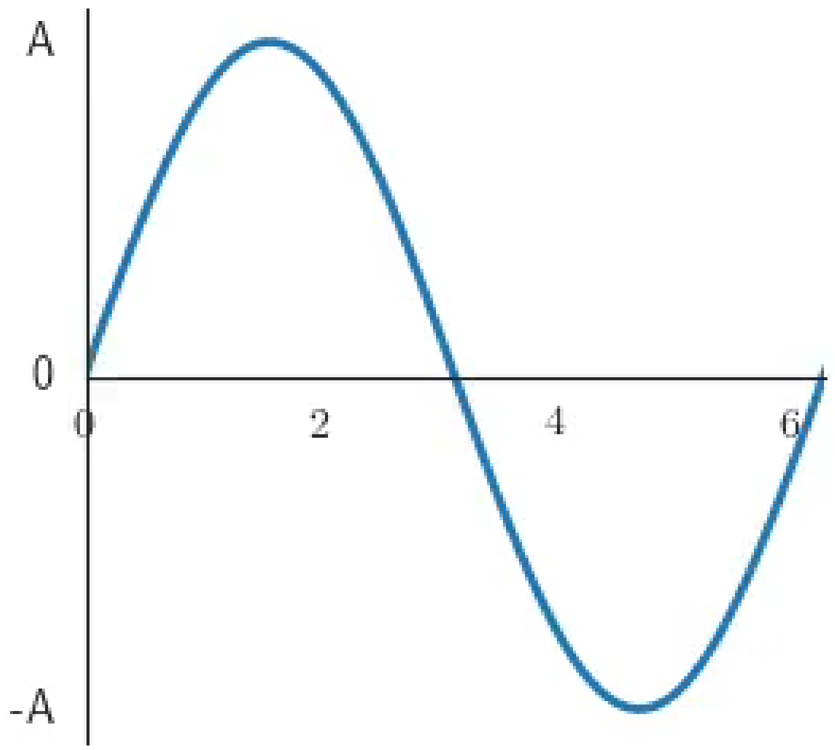
This wave is moving...

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

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

wave speed: $$\frac{\omega}{k} = v$$

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

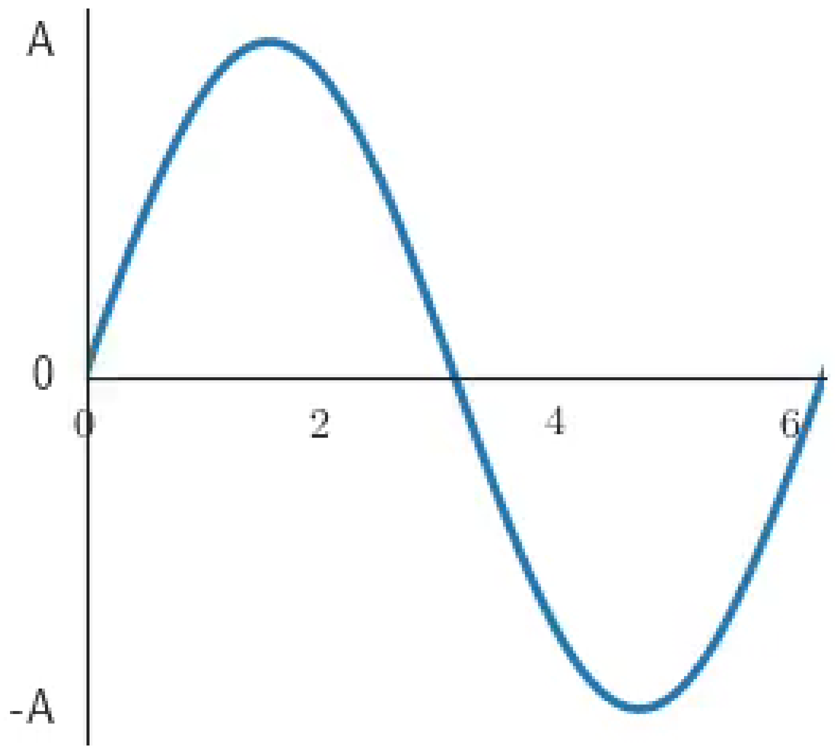
period: $$T = \frac{2\pi}{\omega}$$

$$v = \lambda f$$

frequency: $$\omega = 2\pi f$$

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

wavenumber

angular frequency

phase offset

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?

Waves transport energy

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

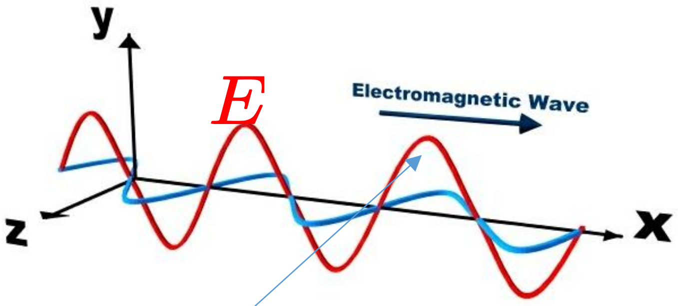
Sunlight intensity is about 1000 W/m^2 at Earth's surface. What is the approximate energy absorbed by a *perfect* 30 cm x 30 cm solar panel during a 10 second interval?

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

Wave amplitude

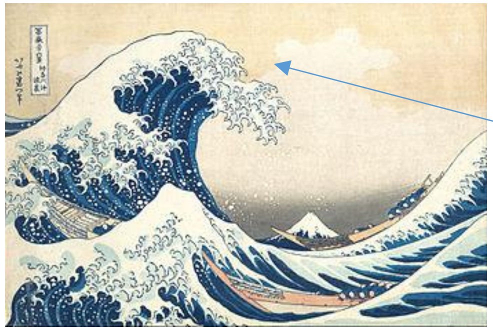
$$y(x,t) = \ldots$$

- 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



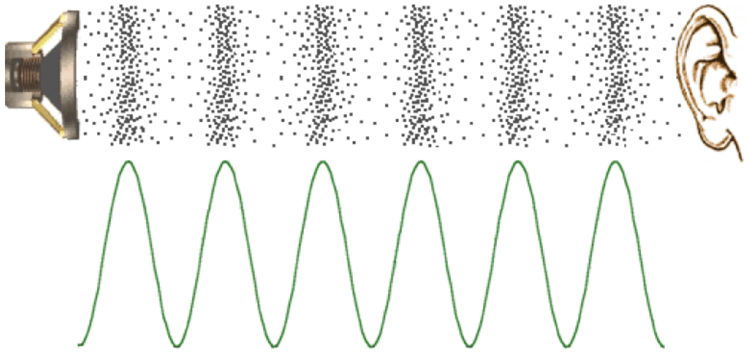
$$A = 700\ \mathrm{N/C}$$

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



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

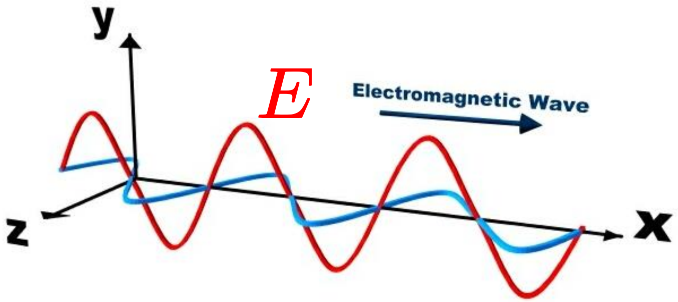
$$A = 1\ \mathrm{Pa} = 1\ \mathrm{N/m^2}$$



Intensity is proportional to the square of the amplitude

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

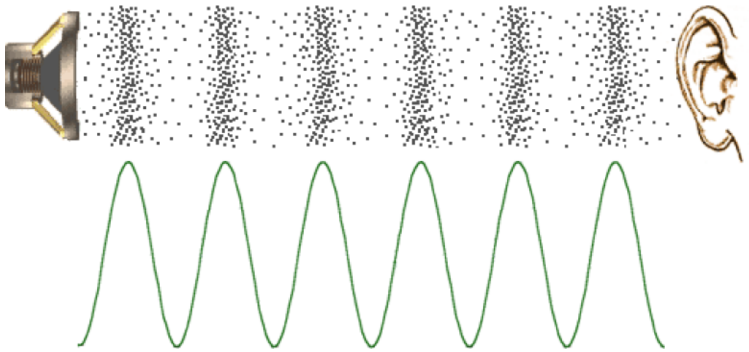
approximately



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

exactly

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



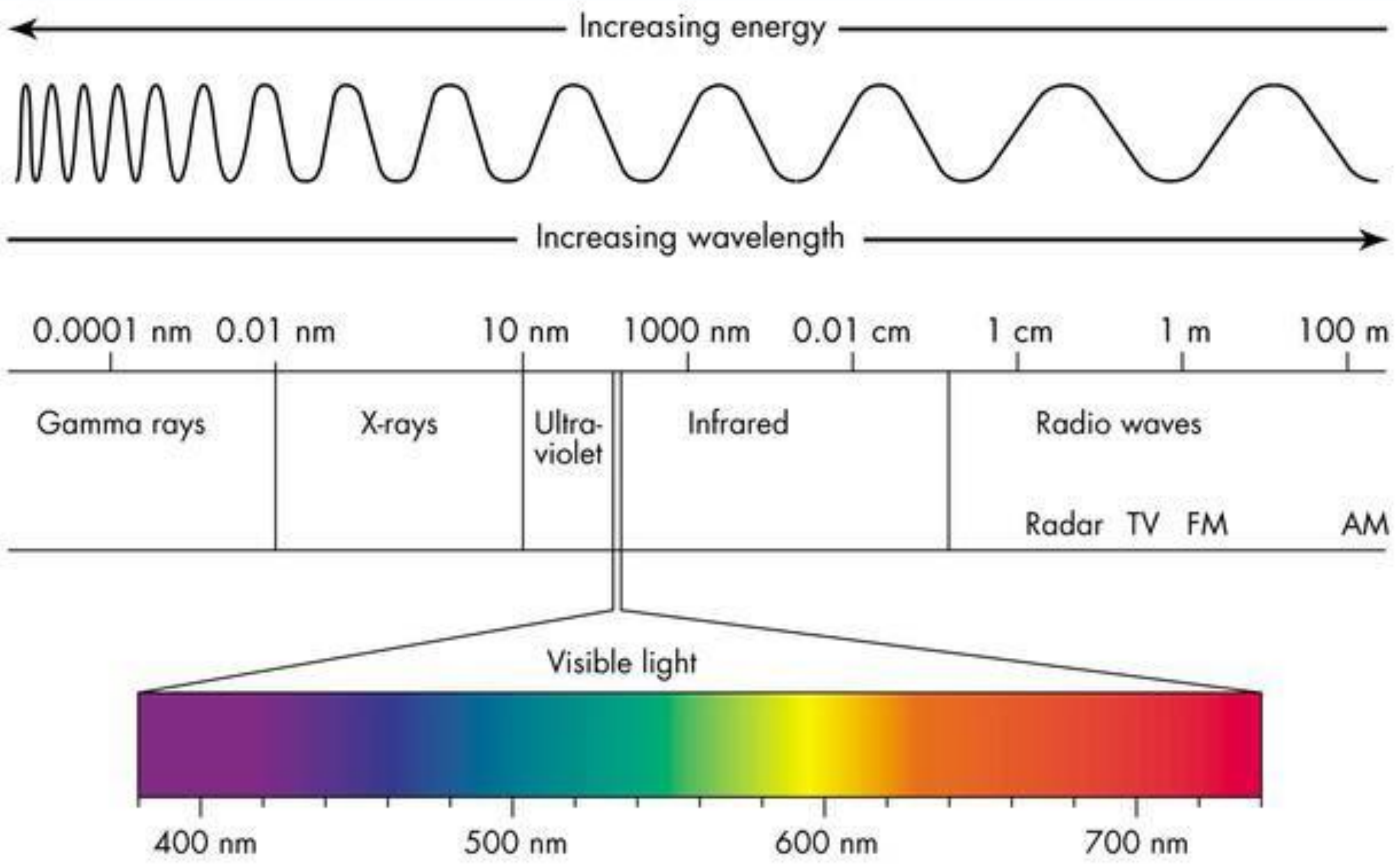
$I \propto (\text{max pressure})^2$

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

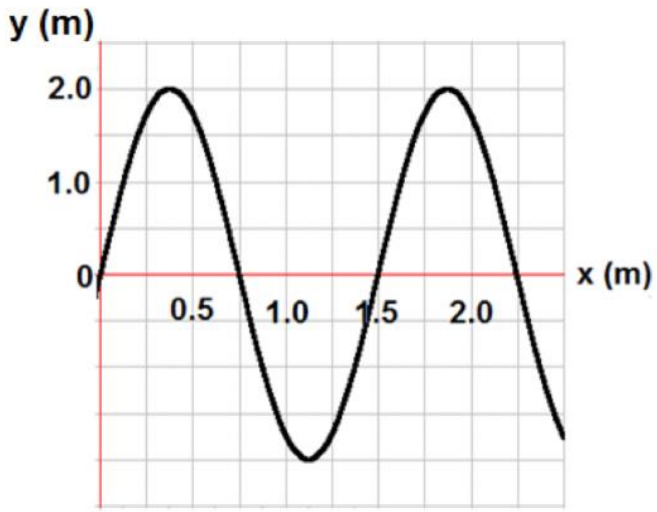
Amplitude	A
Average Intensity	$I \propto \frac{A^2}{2}$
Frequency	f
Wavelength	λ
Phase offset	ϕ
Period	$T = \frac{1}{f}$
Velocity	$v = \lambda f$
Wave number	$k = \frac{2\pi}{\lambda}$
Angular frequency	$\omega = 2\pi f$

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

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

Sample problem

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



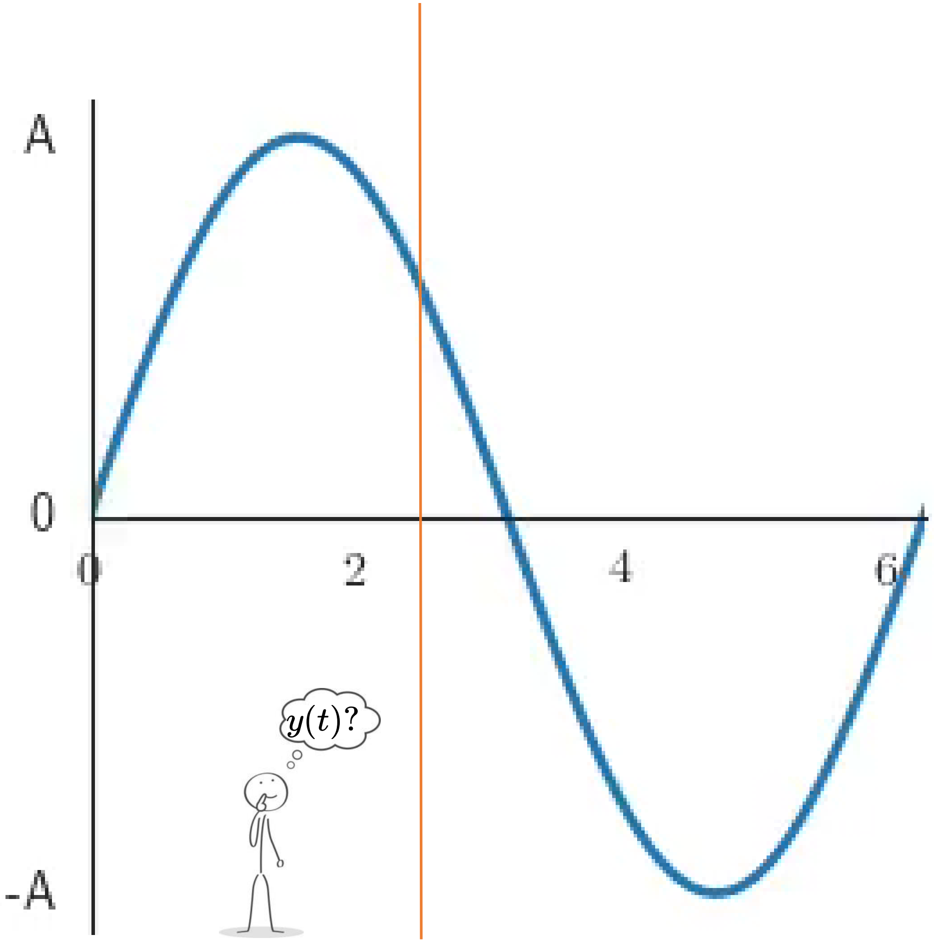
What is the amplitude of oscillations of this wave at this instant?

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

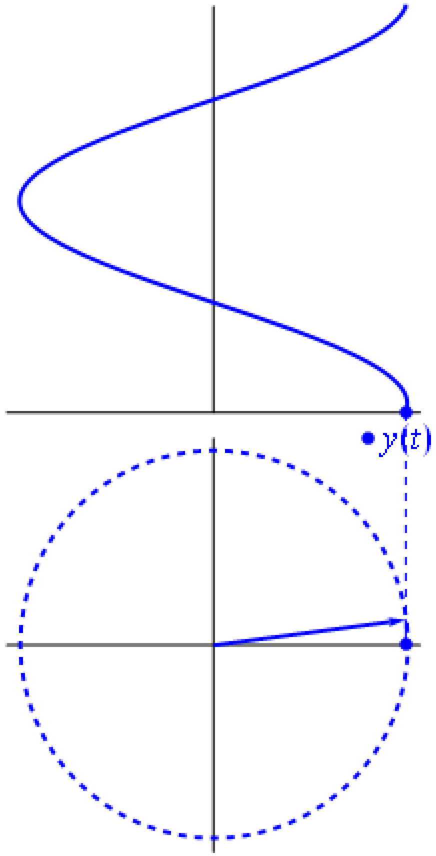
What is the speed of the wave if the frequency of oscillation is 12.0 Hz?

- (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

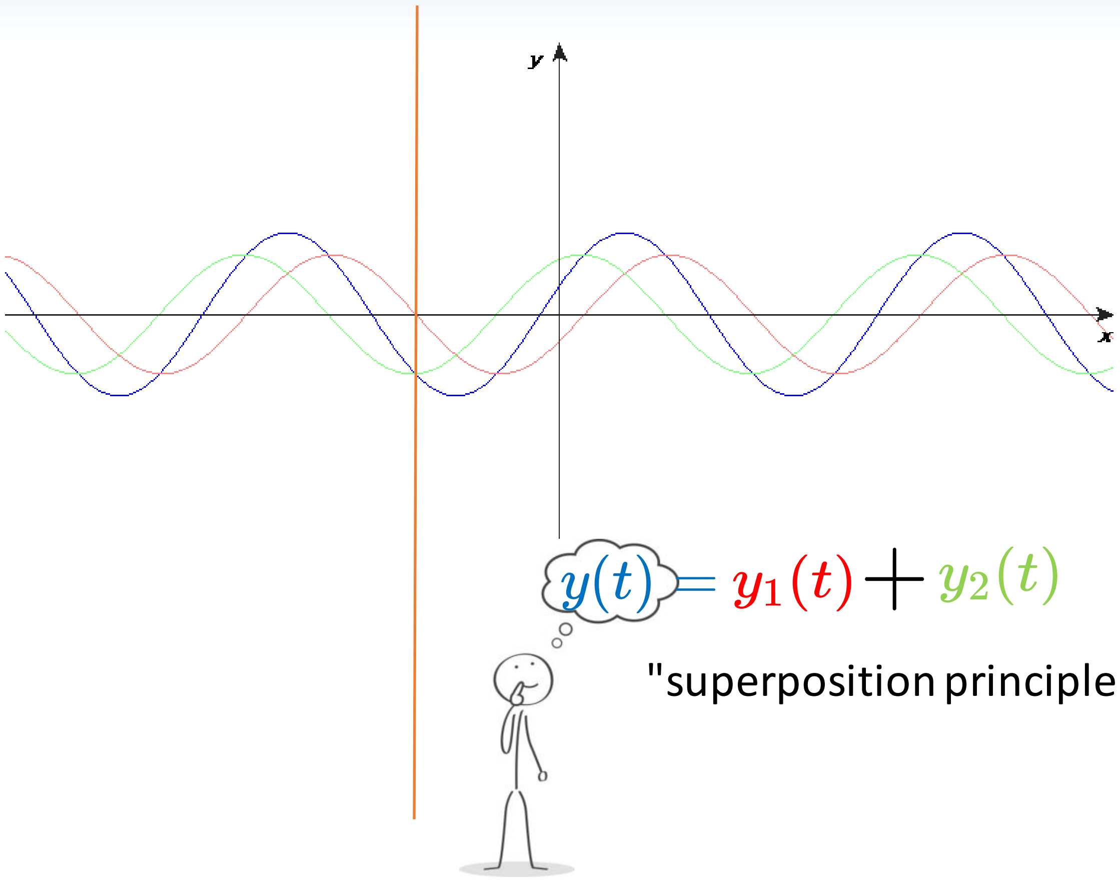
Phasors are a graphical tool for representing and adding harmonically oscillating quantities



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



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