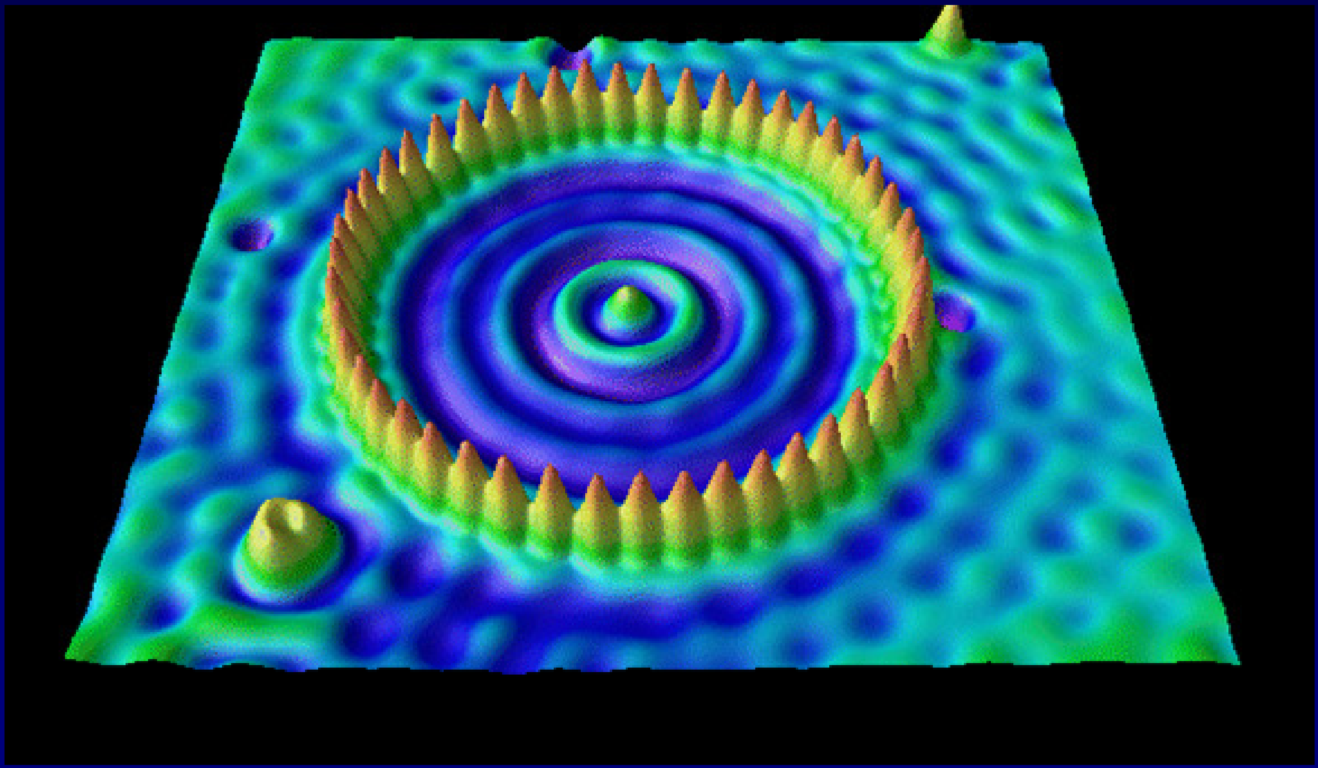
Physics 214

Waves and Quantum Physics



Welcome to Physics 214

Faculty: Lectures A&B: Paul Kwiat
Discussion: Raffi Budakian — Labs: Alexey Bezryadin

All course information is on the web site. Read it !!
courses.physics.illinois.edu/phys214

Format: Active Learning (Learn from Participation)
- Homework: Do it on the web !!
- Lecture: Presentations, demos, & ACTs. Bring your calculator.
- Discussion: Group problem solving. Starts this week
- Lab: Up close with the phenomena. Starts next week
  Prelabs are due at the beginning of lab.

No prelectures!! Instead, Ask the Prof. See the web site.
SmartPhysics – it's the "CheckPoint" feature for each lecture.
This Friday only: Bonus point for doing the survey.

Textbook: Young and Freedman. Assignments on Syllabus page

James Scholar Students: See link on course website for information.

WWW and Grading Policy

Almost all course information is on the web site

Here you will find: courses.physics.illinois.edu/phys214

- announcements
- course description & policies
- syllabus (what we're doing every week) ⇐ Look at it !!
- lecture slides
- lab information
- discussion solutions (at the end of the week)
- homework assignments
- sample exams
- gradebook

Need to send us email?
Send it to the right person.
See "contact Info"
on the web page.

The official grading policy (See the course description for details)

- Your grade is determined by exams, homework, quizzes, labs, and lecture.
- The lowest quiz score will be dropped. No other scores will be dropped.
- Letter grade ranges are listed on the web.
- Excused absence forms must be turned in within one week of your return to class.
  If you miss too many classes, whether excused or not, you will not get course credit!!

Lectures Use iClickers

See "iClickers" on the web page.

- We'll award a point for every lecture attended, up to 15 maximum.

  "Attended" $\equiv$ responded to $\geq$1/2 of questions. We don't grade your response.

  It doesn't matter which lecture you attend.
- Batteries: If the battery-low indicator flashes, you still have several lecture's worth of energy, i.e., *NO iClicker EXCUSES.*
- Everyone will get iClicker credit for lecture 1, so:
  - Don't worry if you don't have yours today.
  - Don't assume that credit in the grade book for lecture 1 means you've properly registered (wait ~2 weeks to see).
- Once again: *NO iClicker EXCUSES.*

iClicker Practice

Act 0:

What is your major?

A. Engineering (not physics)
B. Physics
C. Chemistry
D. Other science
E. Something else

Three Lectures per Week

Unlike P211 and P212, we have three lectures per week (MWF):

- MW lectures will mostly focus on concepts, ACTS, and demos.
- Friday lectures will focus more on problem solving and question/answer.

If you are confused by something in a MW lecture (and didn't ask during that lecture), ask about it on Friday.

Or better still, submit your question to the SmartPhysics AskTheProfessor Checkpoint for the next lecture.

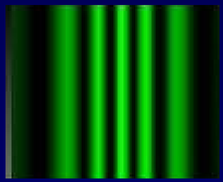
What is 214 all about? (1)

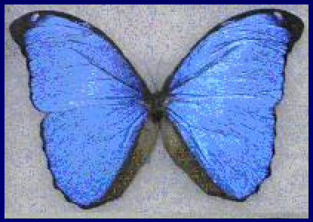
Many physical phenomena of great practical interest to engineers, chemists, biologists, physicists, *etc*. were not in Physics 211 or 212.

Wave phenomena (the first two weeks)

- Classical waves (brief review)
  - Sound, electromagnetic waves, waves on a string, etc.
  - Traveling waves, standing waves
- Interference and the principle of superposition
  - Constructive and destructive interference
  - Amplitudes and intensities
  - Colors of a soap bubble, . . . (butterfly wings!)
- Interferometers
  - Precise measurements, e.g., Michelson Interferometer
- Diffraction:
  - Optical Spectroscopy - diffraction gratings
  - Optical Resolution - diffraction-limited resolution of lenses, …

Interference!





What is 214 all about? (2)

Quantum Physics

Particles act like waves!

Particles (electrons, protons, nuclei, atoms, . . .)
interfere like classical waves, *i.e.*, wave-like behavior

Particles have only certain "allowed energies" like waves on a piano

The Schrodinger equation for quantum waves describes it all.

Quantum tunneling
Particles can "tunnel" through walls!

QM explains the nature of chemical bonds, molecular structure, solids, metals, semiconductors, lasers, superconductors, . . .

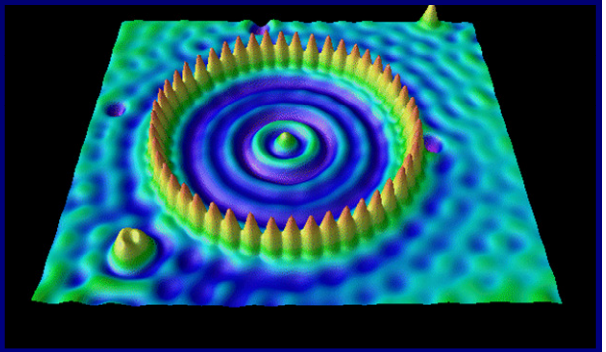
Waves act like particles!

When you observe a wave (*e.g.*, light), you find "quanta" (particle-like behavior).

Instead of a continuous intensity, the result is a probability of finding quanta!

Probability and uncertainty are part of nature!

Scanning tunneling microscope (STM) image of atoms and electron waves



Today

- Wave forms
  The harmonic waveform

- Amplitude and intensity

- Wave equations (briefly)

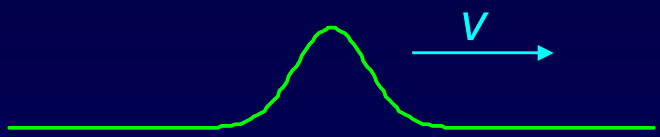
- Superposition

We'll spend the first two weeks on wave phenomena and applications.

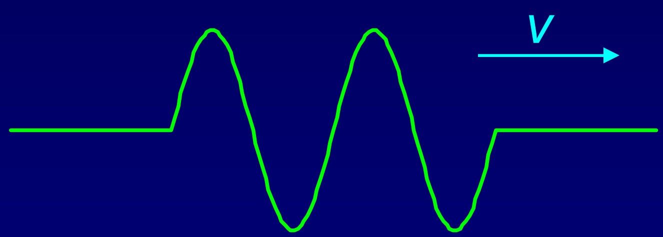
Wave Forms

We can have all sorts of waveforms:

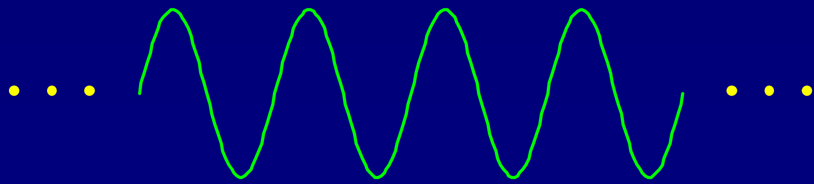
Pulses caused by brief disturbances of the medium



Wavepackets: like harmonic waves, but with finite extent.



We usually focus on harmonic waves that extend forever. They are useful because they have simple math, and accurately describe a lot of wave behavior.



Also called “sine waves”

The Harmonic Waveform (in 1-D)

$$y(x,t) = A\cos\left(\frac{2\pi}{\lambda}(x - vt)\right) \equiv A\cos(kx - 2\pi ft) \equiv A\cos(kx - \omega t)$$

y is the displacement from equilibrium.

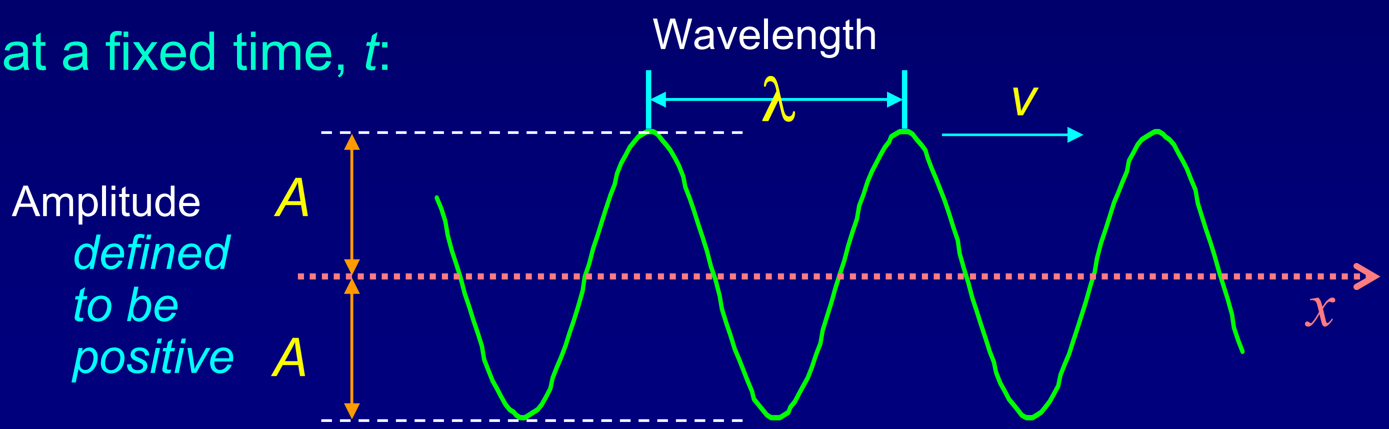
A function of two variables: x and t.

$v \equiv$ speed $\qquad A \equiv$ amplitude (defined to be positive)

$\lambda \equiv$ wavelength $\qquad k \equiv \dfrac{2\pi}{\lambda} \equiv$ wavenumber

$f \equiv$ frequency $\qquad \omega \equiv 2\pi f \equiv$ angular frequency

A snapshot of y(x) at a fixed time, t:



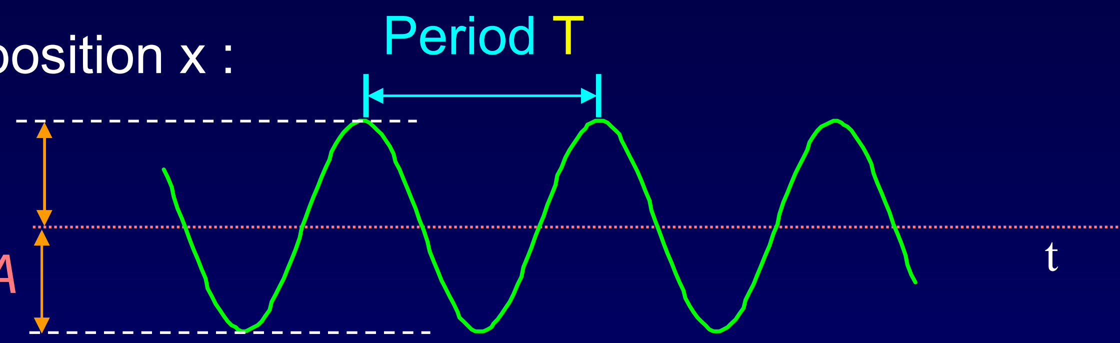
This is review from Physics 211/212.
For more detail see Lectures 26 and 27 on the 211 website.

Wave Properties

Period: The time T for a point on the wave to undergo one complete oscillation.

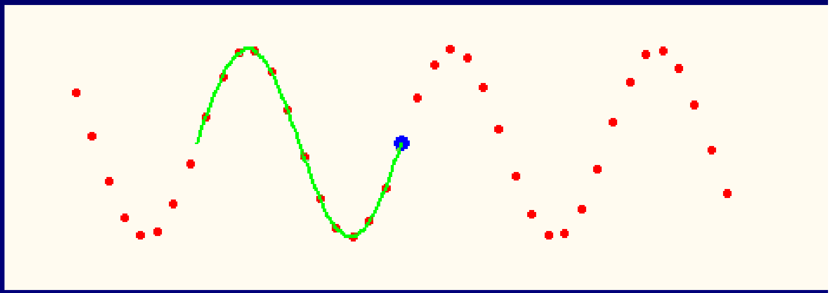
For a fixed position x :

Amplitude A



Speed: The wave moves one wavelength, λ, in one period, T. So, its speed is:

$$\boxed{v = \frac{\lambda}{T} = \lambda f}$$



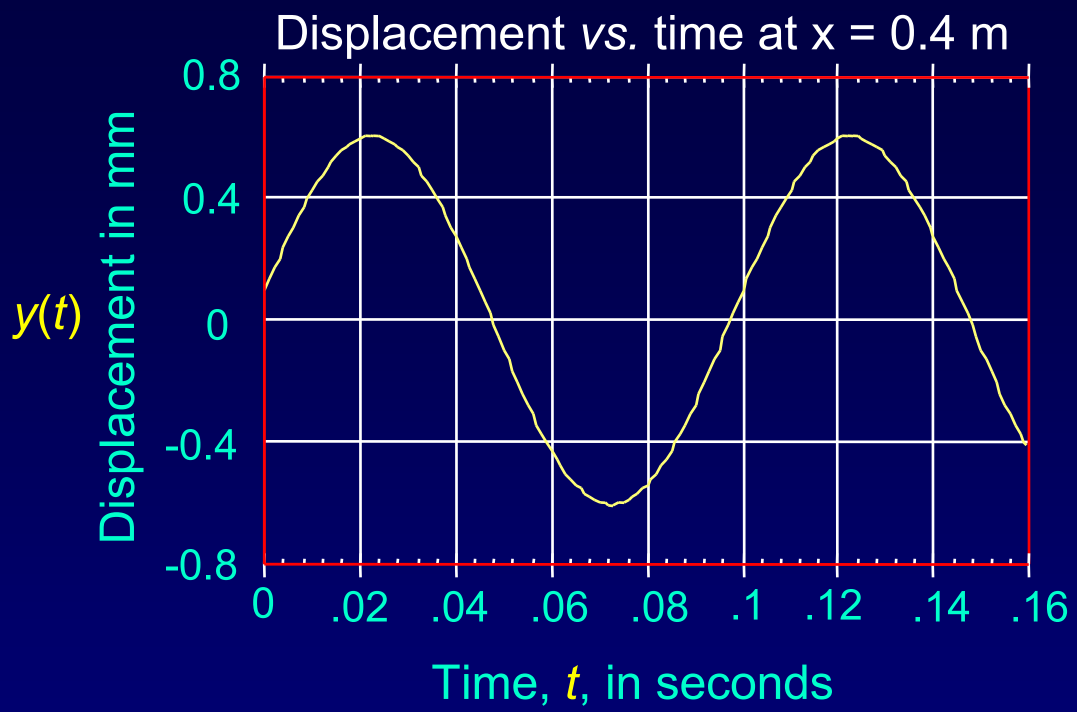
Frequency: $f = 1/T =$ cycles/second.

Movie (tspeed)

Angular frequency: $\omega = 2\pi f =$ radians/second

Be careful: Remember the factor of 2π

Wave Properties Example

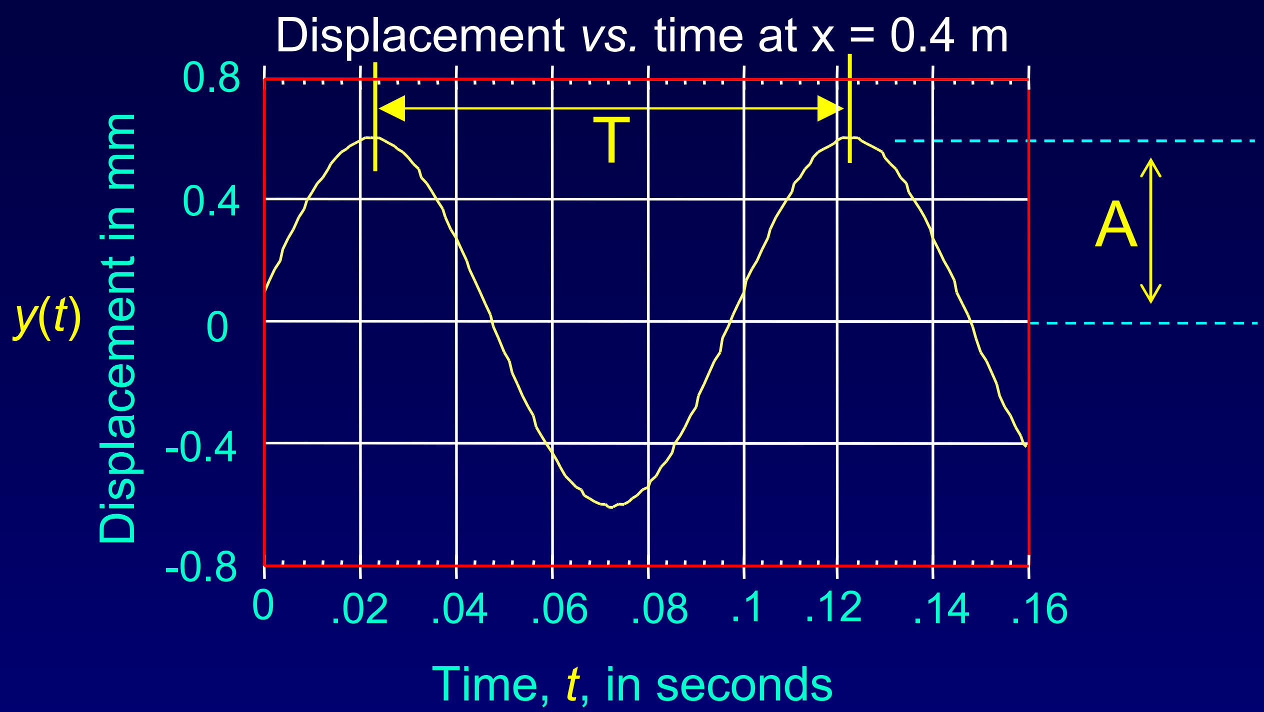


What is the amplitude, A, of this wave?

What is the period, T, of this wave?

If this wave moves with a velocity v = 18 m/s, what is the wavelength, λ, of the wave?

Solution



What is the amplitude, A, of this wave? A = 0.6 mm

What is the period, T, of this wave? T = 0.1 s

If this wave moves with a velocity v = 18 m/s, what is the wavelength, λ, of the wave?

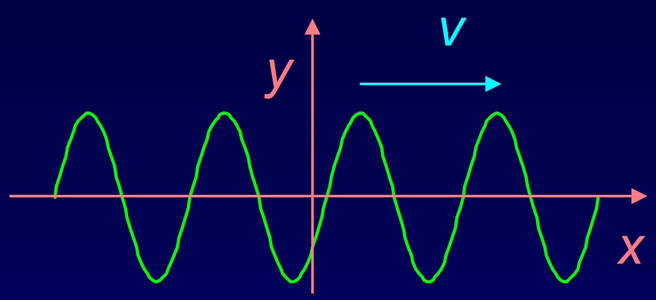
$v = f\lambda = \lambda/T$

$\lambda = vT = 1.8$ m

Note that λ is not displayed in a graph of $y(t)$.

Act 1

A harmonic wave moving in the positive x direction can be described by the equation
$y(x,t) = A \cos(kx - \omega t)$.



Which of the following equations describes a harmonic wave moving in the negative x direction?

a) $y(x,t) = A \sin(kx - \omega t)$

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

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

Solution

A harmonic wave moving in the positive x direction can be described by the equation
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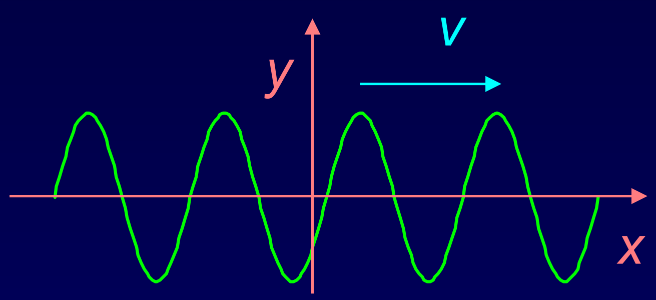

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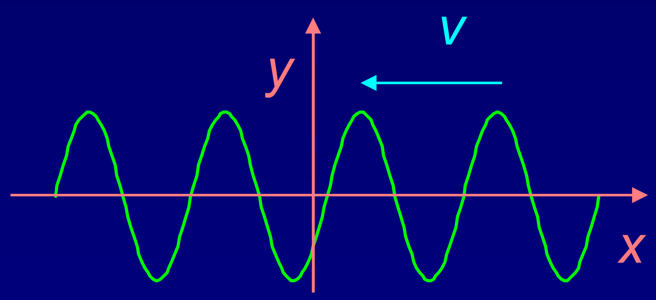


In order to keep the argument constant, if *t* increases, *x* must decrease.

The Wave Equation

For any function, f:
$f(x - vt)$ describes a wave moving in the positive x direction.
$f(x + vt)$ describes a wave moving in the negative x direction.

The appendix has a discussion of traveling wave math.

You will do some problems in discussion.

What is the origin of these functional forms?
They are solutions to a wave equation:

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

The harmonic wave, $f = \cos(kx \pm \omega t)$, satisfies the wave equation.
(You can verify this.)

Examples of wave equations:

Sound waves:
$$\frac{d^2 p}{dx^2} = \frac{1}{v^2}\frac{d^2 p}{dt^2}$$
p is pressure

Electromagnetic waves:
See P212, lecture 22, slide 17
$$\frac{d^2 E_x}{dz^2} = \frac{1}{c^2}\frac{d^2 E_x}{dt^2}$$
Also E_y B_x and B_y

Amplitude and Intensity

Intensity: How *bright* is the light? How *loud* is the sound?

Intensity tells us the energy carried by the wave.

Intensity is proportional to the square of the amplitude.

	Amplitude, *A*	Intensity, I
Sound wave:	peak differential pressure, p_o	power transmitted/area (loudness)
EM wave:	peak electric field, E_o	power transmitted/area (brightness)

For harmonic waves, the intensity is always proportional to the time-average of the power. The wave oscillates, but the intensity does not.

Example, EM wave: $$I = \frac{\langle E^2 \rangle}{\mu_o c} = \frac{1}{\mu_o c}\frac{1}{2}E_0^2$$

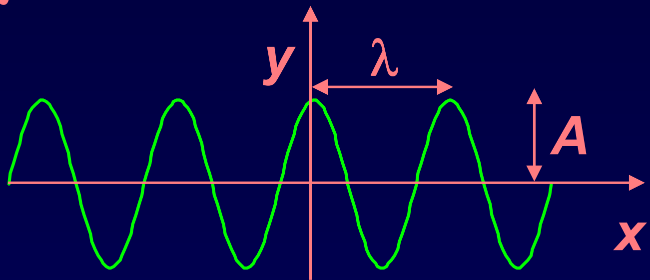
For a harmonic wave, the time average, denoted by the <>, gives a factor of 1/2.

We will usually calculate ratios of intensities. The constants cancel.

In this course, we will ignore them and simply write:

$$\boxed{I = A^2 \quad \text{or} \quad A = \sqrt{I}}$$

Wave Summary



The formula $y(x,t) = A\cos(kx - \omega t)$
describes a harmonic plane wave
of amplitude *A* moving in the +*x* direction.

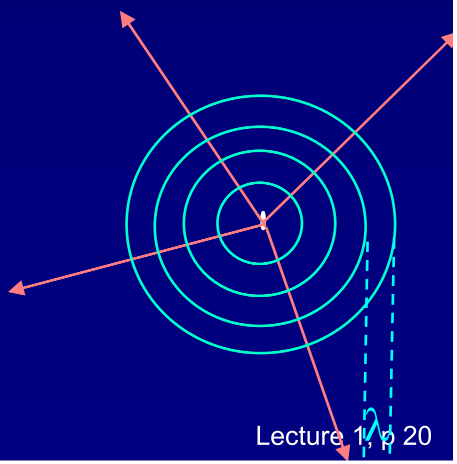
For a wave on a string, each point on the wave oscillates in the *y* direction with simple harmonic motion of angular frequency ω.

The wavelength is $\lambda = \dfrac{2\pi}{k}$; the speed is $v = \lambda f = \dfrac{\omega}{k}$

The intensity is proportional to the square of the amplitude: $I \propto A^2$

Sound waves or EM waves that are created from a point source are spherical waves, i.e., they move radially from the source in all directions.

- These waves can be represented by circular arcs:
- These arcs are surfaces of constant phase (e.g., crests)
- **Note: In general for spherical waves the intensity will fall off as $1/r^2$, i.e., the amplitude falls off as 1/r. However, for simplicity, we will neglect this fact in Phys. 214.**



Superposition

A key point for this course!

Use the fact that $$\frac{d(y+z)}{dx} = \frac{dy}{dx} + \frac{dz}{dx}$$

The derivative is a "linear operator".

Consider two wave equation solutions, h_1 and h_2:

$$\frac{\partial^2 h_1}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 h_1}{\partial t^2} \quad \text{and} \quad \frac{\partial^2 h_2}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 h_2}{\partial t^2}$$

Add them: $$\frac{\partial^2 (h_1 + h_2)}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 (h_1 + h_2)}{\partial t^2}$$

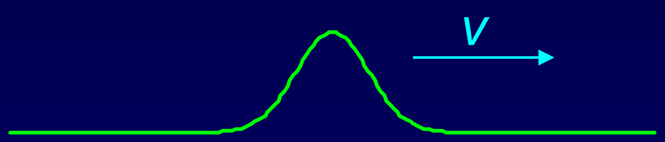
$h_1 + h_2$ is also a solution !!

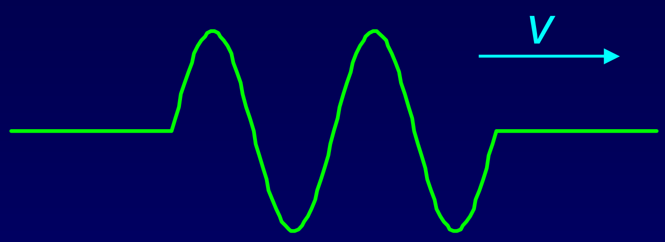
In general, if h_1 and h_2 are solutions then so is $ah_1 + bh_2$.

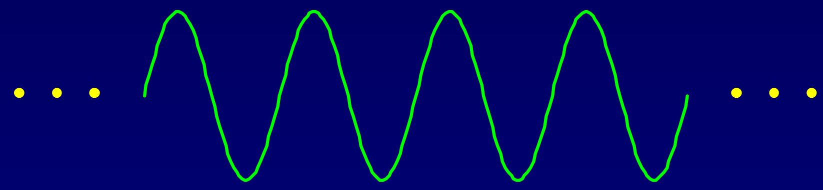
This is superposition. It is a very useful analysis tool.

Wave Forms and Superposition

We can have all sorts of waveforms, but thanks to superposition, if we find a nice simple set of solutions, easy to analyze, we can write the more complicated solutions as superpositions of the simple ones.







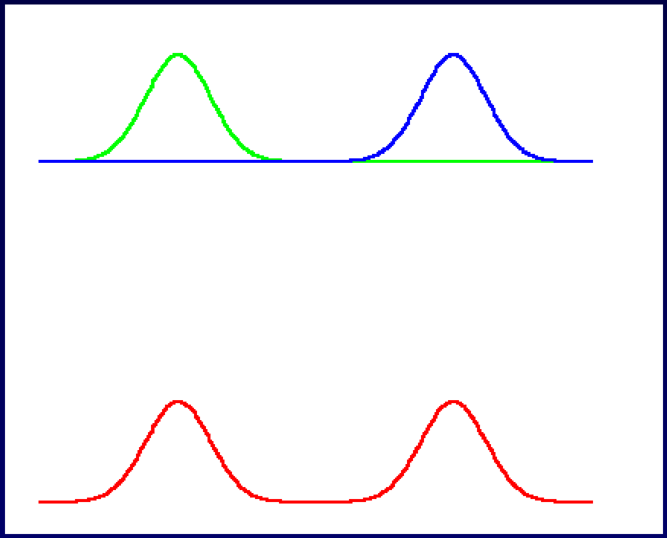
It is a mathematical fact that any reasonable waveform can be represented as a superposition of harmonic waves. This is Fourier analysis, which many of you will learn for other applications.

We focus on harmonic waves, because we are already familiar with the math (trigonometry) needed to manipulate them.

Superposition Example

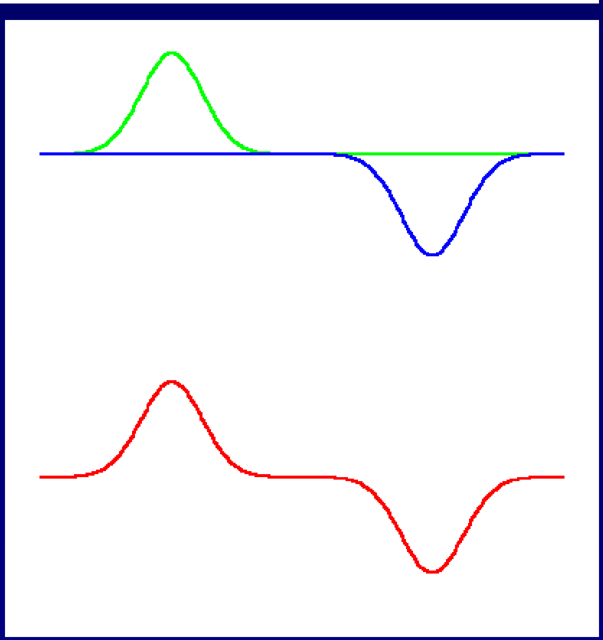
Q: What happens when two waves collide?

A: Because of superposition, the two waves pass through each other unchanged! The wave at the end is just the sum of whatever would have become of the two parts separately.



Superposition is an exact property for:

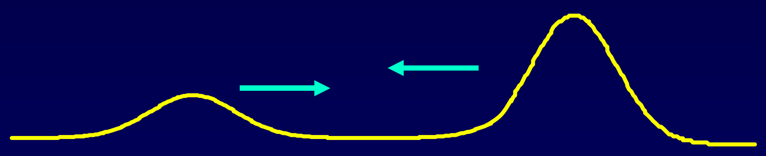
- Electromagnetic waves in vacuum.
- Matter waves in quantum mechanics.
- This has been established by experiment.



Many (but not all) other waves obey the principle of superposition to a high degree, e.g., sound, guitar string, etc.

Act 2

Pulses 1 and 2 pass through each other.
Pulse 2 has four times the peak intensity of pulse 1, i.e., $I_2 = 4\ I_1$.



NOTE: These are not harmonic waves, so the time average isn't useful.
By "peak intensity", we mean the square of the peak amplitude.

1. What is the maximum possible total combined intensity, I_{max}?

   a) $4\ I_1$

   b) $5\ I_1$

   c) $9\ I_1$

2. What is the minimum possible intensity, I_{min}?

   a) 0

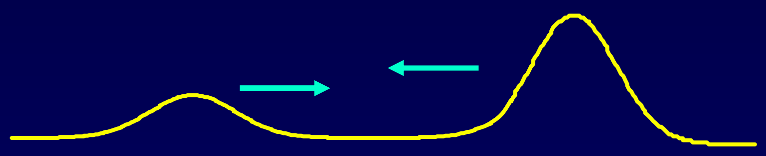
   b) I_1

   c) $3\ I_1$

This happens when one of the pulses is upside down.

Solution

Pulses 1 and 2 pass through each other.
Pulse 2 has four times the peak intensity of pulse 1, i.e., $I_2 = 4\ I_1$.



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1. What is the maximum possible total combined intensity, I_{max}?

a) $4\ I_1$

b) $5\ I_1$

c) $9\ I_1$

Add the amplitudes, then square the result:

$$A_2 = \sqrt{I_2} = \sqrt{4I_1} = 2\sqrt{I_1} = 2A_1$$

$$I_{tot} = \left(A_{tot}\right)^2 = \left(A_1 + A_2\right)^2 = \left(A_1 + 2A_1\right)^2 = 9A_1^2 = 9I_1$$

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a) 0

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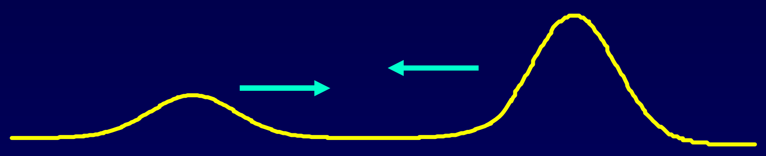

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a) 0

b) I_1

c) $3\ I_1$

Now, we need to subtract:

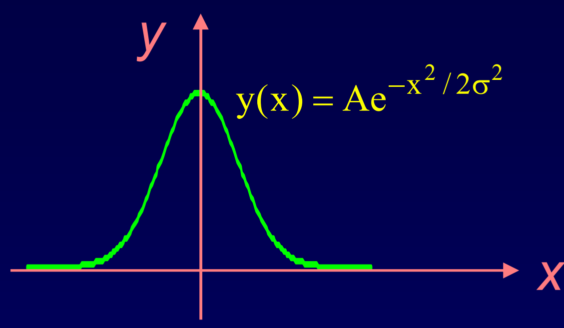
$$I_{tot} = \left(A_{tot}\right)^2 = \left(A_1 - A_2\right)^2 = \left(A_1 - 2A_1\right)^2 = A_1^2 = I_1$$

Next time:
Interference of waves
A Consequence of superposition

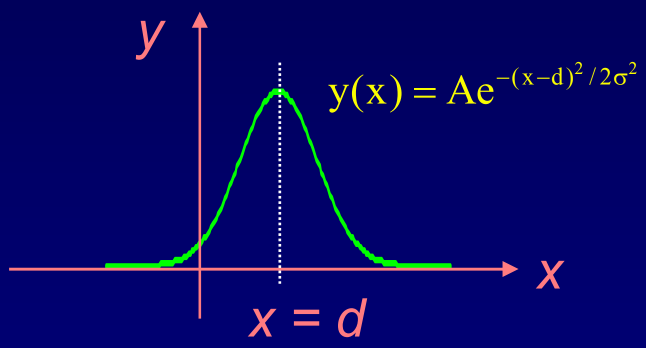
- Read Young and Freeman Sections 35.1, 35.2, and 35.3
- Check the “test your understanding” questions
- Remember Ask-The-Prof bonus survey

Appendix: Traveling Wave Math

Why is $f(x \pm vt)$ a "travelling wave"?
Suppose we have some function $y = f(x)$:



$y = f(x - d)$ is just the same shape shifted a distance d to the right:



Suppose $d = vt$. Then:

- $f(x - vt)$ will describe the same shape moving to the right with speed v.
- $f(x + vt)$ will describe the same shape moving to the left with speed v.