QUIZSTAR was down today – quizlet grade for today dropped
HOMEWORK #1 is due tonight at 11:59 PM
QUIZLET grading: goal is participation – you will get full credit
for the quizlet if you have at least 1 right answer

GET OUT YOUR CLICKERS!
CLICKER: When and where would you prefer office hours?
(a) Sunday 6-7 on Busch
(b) Sunday 6-7 on College Ave
(c) Tuesday 5-6 on Busch
(d) Tuesday 6-7 on College Ave

BEFORE CLASS: read TIP FOR PHASE on upper right board
Hands-on demos: stretched ropes, wave box
3. Which of the following describes $\varphi$ for the SHM in the figure, using $x(t) = A \cos(\omega t + \varphi)$? 

1 pts.

- [ ] A. $-\pi < \varphi < -\pi/2$
- [ ] B. $0 < \varphi < \pi/2$
- [ ] C. $-3\pi/2 < \varphi < -\pi$
- [ ] D. $-\pi/2 < \varphi < 0$
- [ ] Flag this question for later review
Chapter 16

Waves-I
Wave Motion:

A wave is a disturbance that transports energy away from its source.

“Mechanical waves” propagate in a medium (a string, air, a solid...) Wave may propagate over a large distance. But particles of the medium move in a much more localized area.
Wave on a stretched string: Transverse wave

In a transverse wave, the displacement of every oscillating element along the wave is perpendicular to the direction of travel of the wave.
If end is moved in SHM with amplitude $y_m$, angular frequency $\omega$

Each oscillating element executes SHM
Same amplitude $y_m$ and same angular frequency $\omega$
Same frequency $\omega/(2\pi)$ (cycles/second)
Same period $T = 2\pi/\omega$ (time for one cycle)

Amplitude of wave is $y_m$
Angular frequency of wave is $\omega$ (radians/second)
Frequency of wave $f = \omega/(2\pi)$
Period of wave $T = 2\pi/\omega$
If end is moved in SMH with amplitude $y_m$, frequency $\omega$

Each oscillating element executes SHM

**Amplitude** of wave is $y_m$

**Angular frequency** of wave is $\omega$ (radians/second)

**Frequency** of wave $f = \omega/(2\pi)$

**Period** of wave $T = 2\pi/\omega$

At two different points, phase difference

Take a snapshot at $t=0$: sin function with wavelength $\lambda$

$y(x,t=0) = y_m \sin \left(\frac{2\pi}{\lambda} x\right)$

The **wavelength** of the wave is $\lambda$

$k = (2\pi/\lambda)$ is called the **wavenumber**

Three quantities to characterize the wave: amplitude, angular frequency and wavelength
y(x,t) = y_m \sin (kx-\omega t) 
or y(x,t) = y_m \sin (kx+\omega t)

y(x,t) = y_m \sin (kx-\omega t)
To keep kx-\omega t constant, t \to t+\Delta t means x \to x+(\omega/k)\Delta t
wave traveling to the right with speed \( v = \Delta x/\Delta t = \omega/k \)

y(x,t) = y_m \sin (kx+\omega t)
wave traveling to the left
In one period, the pattern returns to itself
Crest has moved one wavelength to the right

Wavespeed \( v = \frac{\text{wavelength}}{\text{period}} = \frac{\lambda}{T} \)

Wavespeed \( v = \frac{(2\pi/k)}{(2\pi/\omega)} = \frac{\omega}{k} \)
PHET demo “experiment”
Measure the dependence of wave speed on frequency
PHET demo “experiment”
Measure the dependence of wave speed on frequency

For a given string,
WAVESPEED IS INDEPENDENT OF FREQUENCY

To understand why this is true, need to apply Newton’s 2nd Law to get the equation of motion for the stretched string
Producing SHM: review

You already know that a particle executes SHM if there is a restoring force proportional to the displacement.

Start from Newton’s 2nd Law $F = ma$:
$m \frac{d^2y}{dt^2} = -ky$

solutions are
$y(t) = A \cos (\omega t + \phi)$
SHM with $\omega^2 = k/m$
Each oscillating element obeys Newton’s 2\textsuperscript{nd} law $F = m \frac{d^2y}{dt^2}$

Mass from $x$ to $x+dx$ : $\mu \, dx = (M/L) \, dx$ (assume uniform string)

Force: difference in the $y$ component of the tension $\tau$
Change in slope from $x$ to $x + dx$

$F = -\tau \frac{d^2y}{dx^2} \, dx$

From Newton’s 2\textsuperscript{nd} Law we get the wave equation

$-\tau \frac{d^2y}{dx^2} \, dx = \mu \, dx \frac{d^2y}{dt^2}$
$-\tau \frac{d^2y}{dx^2} = \mu \frac{d^2y}{dt^2}$

our form for $y(x,t)$ can solve this equation
$y(x,t) = y_m \sin (kx-\omega t+\phi)$ or $y(x,t) = y_m \sin (kx-\omega t+\phi)$
if $(\omega/k)^2 = \tau/\mu$ so wavespeed is $(\tau/\mu)^{1/2}$
In the simulation, the time taken for a crest of the wave to travel the length of the string depends on

- A. both the amplitude and the frequency
- B. the amplitude but not the frequency
- C. the frequency but not the amplitude
- D. neither the frequency nor the amplitude

Flag this question for later review
The wave equation arises in many physical contexts, not just transverse motion of a stretched string

1. **Mechanical waves.** They are governed by Newton’s laws, and they can exist only within a material medium, such as water, air, and rock. *Eg:* water waves, sound waves, and seismic waves.

2. **Electromagnetic waves.** These waves require no material medium to exist. All electromagnetic waves travel through a vacuum at the same exact speed $c = 299,792,458 \text{ m/s}$. *Eg:* visible and ultraviolet light, radio and television waves, microwaves, x-rays, and radar.

3. **Quantum mechanical waves.**
An important property of the wave equation

\[-\tau \frac{d^2 y}{dx^2} = m \frac{d^2 y}{dt^2}\]

It is linear

Start with a solution \( y_1(x,t) \)

Multiply by a constant \( C \) \( y_1(x,t) \) – still a solution

Add two solutions \( y_1(x,t) + y_2(x,t) \) – still a solution
Consider two waves with
same amplitude, same angular frequency, same direction
different phase

\[ y_1(x,t) = y_m \sin (kx-\omega t+\phi_1) \]
\[ y_2(x,t) = y_m \sin (kx-\omega t+\phi_2) \]

The wave
\[ y(x,t) = y_1(x,t) + y_2(x,t) \] also solves the wave equation for the string
and is a possible wave motion

\[ \sin(a) + \sin(b) = 2 \sin((a+b)/2) \cos((a-b)/2) \]
\[ y(x,t) = [2 y_m \cos((\phi_1 - \phi_2)/2)] \sin (kx-\omega t+(\phi_1 + \phi_2)/2) \]
sin wave with same angular frequency and direction
The phase difference \( \phi_1 - \phi_2 \) determines the amplitude
Can measure phase difference in degrees, radians or wavelengths (= distance the two waves are shifted in a snapshot)
Consider two waves with 
same amplitude, same angular frequency, same phase 
 opposite direction 

\[ y_1(x,t) = y_m \sin (kx-\omega t+\phi) \]
\[ y_2(x,t) = y_m \sin (kx+\omega t+\phi) \]

The wave 
\[ y(x,t) = y_1(x,t) + y_2(x,t) \] also solves the wave equation for the string 
and is a possible wave motion 

\[ \sin(a) + \sin(b) = 2 \sin((a+b)/2) \cos((a-b)/2) \]

\[ y(x,t) = [2 y_m \cos(\omega t)] \sin (kx+\phi) \]
not a sin wave, but a “standing wave” 
All points oscillate in phase, amplitude depends on x
STANDING WAVE ON A ROPE DEMO/PHET

In PHET, you need to turn on the minimum amount of damping (I forgot to do this in class, which led to distracting results) and use fixed end. Then by careful tuning of the frequency you might be able to get motion in which there are beads that don’t move (nodes in a standing wave)

https://phet.colorado.edu/sims/html/wave-on-a-string/latest/wave-on-a-string_en.html