Today:

- Sound Wave Intensity and the decibel system
- Wave Interference: The Principle of Superposition
- Constructive and Destructive Interference
- Beats
- Reflection and Refraction
- Standing Waves
- Musical Instruments

**i-Clicker Discussion Question**

Two wave pulses on a string approach each other at speeds of 1 m/s. How does the string look at $t = 3$ s?

A. ![Graph A](image1)
B. ![Graph B](image2)
C. ![Graph C](image3)
D. ![Graph D](image4)
Class 23 Preclass Quiz on MasteringPhysics

- This was due this morning at 8:00am

- 84% of students got: Two wave pulses pass each other on a string. The pulse traveling toward the right has positive amplitude, whereas the pulse traveling toward the left has equal amplitude in the negative direction. What happens when they occupy the same region of space at the same time? **Destructive interference occurs.**

- 93% of students got: A pulse travels along a stretched string, one end of which is fixed to a wall. When the pulse encounters the wall, it is reflected. The reflected pulse **has the same shape as the initial pulse, but is inverted.**

Class 23 Preclass Quiz on MasteringPhysics

- 45% of students got: Shown is an animation of a standing wave. The standing wave is represented by the white line which is oscillating with the higher amplitude. It is due to the superposition of two traveling waves each of smaller amplitude, one traveling toward the left, and the other traveling toward the right. **Fourth harmonic.**

- 71% of students got: A standing wave is established in an organ pipe that is closed at one end. **A displacement antinode is located at the open end, and a displacement node is located at the closed end.**
Class 23 Preclass Quiz Student Comments

▪ “Is there a class on Wednesday due to "Make-up Monday" from the classes missed on Thanksgiving?”
▪ Harlow answer: Yes. Wednesday is the 24th class of this 12-week semester.
▪ “This is the last time I'll have an opportunity to have a comment posted, and the chances of this one going up is pretty much nonexisant. Woe is me. :""""(""
▪ Harlow comment: Not true – there’s still one more chance!
▪ “I'm a third year chemistry specialist and this is my hardest class! Chin-up, first years! It gets better!”
▪ “Is dispersion and Doppler effect going to be on the finals?”
▪ Harlow answer: Yes and no. We officially skipped Doppler effect. Dispersion is mentioned in section 14.5, although I did not emphasize it in class. Basically it is just when the speed of a wave depends on the wave frequency.

Class 23 Preclass Quiz Student Comments

▪ “You said in the pre-class video that in a standing wave, each point would be oscillating with simple harmonic motion up and down, implying that each particle in the string would oscillate a certain amplitude A above and below the equilibrium point. But won't the nodes not oscillate as they are always at equilibrium? So is that statement not then false?”
▪ Harlow comment: You’re right! I should rephrase: each point is oscillating with S.H.M. except the nodes!
Class 23 Preclass Quiz Student Comments

- “This is a little far back but what is rolling friction exactly? I was looking at a question to do with banked curves with friction and I wasn’t really sure how it applied.”
- **Harlow answer:** There are two kinds of friction covered in this course:
  - **kinetic** (slipping objects)
  - **static** (not slipping objects)
- If something is “rolling without slipping” then we use **static**, as needed to accelerate the object. (ie banked curves)
- There is a third kind of friction called “rolling friction” which slows down rolling objects, but it is not covered in this course.

Class 23 Preclass Quiz Student Comments

- “A hypothetical planet has a mass one-third of and a radius three times that of Earth. What is the acceleration due to gravity on the planet in terms of \( g \), the acceleration due to gravity on Earth?”
- **Harlow answer:** \( F = m \cdot g = \frac{GMm}{r^2} \) so if \( M \) goes down by 1/3 and \( r^2 \) goes up by 9 then \( g \) should be 27 times less (9.8/27).
- “how can you calculate angular frequency in radians/s for an object that’s not moving in circular motion? an example of this is the fish oscillating on a spring in problem set 10”
- **Harlow answer:** By definition, \( \omega \) is just \( 2\pi f \), or \( 2\pi/T \).
Intensity and Decibels

- Human hearing spans an extremely wide range of intensities, from the *threshold of hearing* at $\approx 1 \times 10^{-12}$ W/m$^2$ (at midrange frequencies) to the *threshold of pain* at $\approx 10$ W/m$^2$.

- If we want to make a scale of loudness, it’s convenient and logical to place the zero of our scale at the threshold of hearing.

- To do so, we define the **sound intensity level**, expressed in **decibels (dB)**, as:

$$\beta = (10 \text{ dB}) \log_{10} \left( \frac{I}{I_0} \right)$$

where $I_0 = 1 \times 10^{-12}$ W/m$^2$.

### Sound Intensity Levels – Representative Values

<table>
<thead>
<tr>
<th>Source</th>
<th>Sound Intensity Level, $\beta$ (dB)</th>
<th>Intensity, $I$ (W/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Military jet aircraft 30 m away</td>
<td>140</td>
<td>$10^2$</td>
</tr>
<tr>
<td>Threshold of pain</td>
<td>120</td>
<td>1</td>
</tr>
<tr>
<td>Elevated train</td>
<td>90</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Busy street traffic</td>
<td>70</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Quiet radio in home</td>
<td>40</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>Average whisper</td>
<td>20</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>Threshold of hearing at 1000 Hz</td>
<td>0</td>
<td>$10^{-12}$</td>
</tr>
</tbody>
</table>
i-Clicker Discussion Question

• A sound level of 10 decibels has 10 times more intensity than a sound level of zero decibels.

• A sound level of 20 decibels has ____ times more intensity than a sound level of zero decibels.

A. 10
B. 20
C. 50
D. 100
E. 200

i-Clicker Discussion Question

• When you turn up the volume on your ipod, the sound originally entering your ears at 50 decibels is boosted to 80 decibels. By what factor is the intensity of the sound has increased?

A. 1 (no increase)
B. 30
C. 100
D. 300
E. 1000
Particles and Waves

- Particles cannot occupy the same space. They **collide**.

- Waves pass right through each other. They **interfere**.


The Principle of Superposition

If two or more waves combine at a given point, the resulting disturbance is the *sum* of the disturbances of the individual waves.

\[ y = y_1 + y_2 \]
Wave Interference

- The pattern resulting from the superposition of two waves is called interference. Interference can be
  - **constructive**, meaning the disturbances **add** to make a resultant wave of **larger** amplitude, or
  - **destructive**, meaning the disturbances **cancel**, making a resultant wave of **smaller** amplitude.

Two overlapped sound waves

![Two overlapped sound waves](image)

Waves and Wave Fronts

- A **wave front** is the locus of all adjacent points at which the **phase** of a wave is the same.
- Spherical wave fronts of sound spread out uniformly in all directions from a point source.
- Electromagnetic waves in vacuum also spread out as shown here.

![Waves and Wave Fronts](image)
Waves in Two and Three Dimensions

\[ y = A \cos(kr - \omega t) \]
Beats

• Periodic variations in the loudness of sound due to interference
• Occur when two waves of similar, but not equal frequencies are superposed.
• Provide a comparison of frequencies
• Frequency of beats is equal to the **difference** between the frequencies of the two waves.

![Image from hyperphysics.phy-astr.gsu.edu/hbase/sound/beat.html](http://hyperphysics.phy-astr.gsu.edu/hbase/sound/beat.html)

Beats

• Applications
  – Piano tuning by listening to the disappearance of beats from a known frequency and a piano key
  – Tuning instruments in an orchestra by listening for beats between instruments and piano tone
Beats

The medium oscillates rapidly at frequency $f_{\text{avg}}$.

- The amplitude is slowly modulated with a frequency $f_{\text{mod}} = (f_1 - f_2)/2$ (red-dashed line).

- Beats are heard at $f_{\text{beat}} = 2f_{\text{mod}} = f_1 - f_2$.

The amplitude is slowly modulated as $2a \cos(\omega_{\text{mod}} t)$.

Clicker Question

Suppose you sound a 1056-hertz tuning fork at the same time you strike a note on the piano and hear 2 beats/second. What is the frequency of the piano string?

A. 1054 Hz  
B. 1056 Hz  
C. 1058 Hz  
D. Either A or C  
E. Either A, B or C
Clicker Question

Suppose you sound a 1056-hertz tuning fork at the same time you strike a note on the piano and hear 2 beats/second. You tighten the piano string very slightly and now hear 3 beats/second. What is the frequency of the piano string?

A. 1053 Hz
B. 1056 Hz
C. 1059 Hz
D. Either A or C
E. Either A, B or C

Reflection of Transverse Wave Pulse

• A pulse traveling to the right on a heavy string attached to a lighter string
• Speed suddenly increases

[Animation courtesy of Dan Russell, Penn State]
Reflection of Transverse Wave Pulse

• A pulse traveling to the right on a light string attached to a heavier string
• Speed suddenly decreases

[Animation courtesy of Dan Russell, Penn State]

Standing Waves on a String

Wiggle the string in the middle.

Reflections at the ends of the string cause waves of equal amplitude and wavelength to travel in opposite directions along the string, which results in a standing wave.
The Mathematics of Standing Waves

According to the principle of superposition, the net displacement of a medium when waves with displacements $D_R$ and $D_L$ are present is

$$y(x, t) = y_R + y_L = a \cos(kx - \omega t) + a \cos(kx + \omega t)$$

We can simplify this by using a trigonometric identity, and arrive at:

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

where

$$A(x) = 2a \sin(kx)$$

For a standing wave, the pattern is not propagating!

Standing Wave:

The superposition of two 1-D sinusoidal waves traveling in opposite directions.

[Animation courtesy of Dan Russell, Penn State]
i-Clicker Discussion Question

What is the wavelength of this standing wave?

A. 0.25 m.
B. 0.5 m.
C. 1.0 m.
D. 2.0 m.
E. Standing waves don’t have a wavelength.

Node Spacing on a String

The nodes and antinodes are spaced $\lambda/2$ apart.

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Recall that the intensity of a wave is proportional to the square of the amplitude: $I \propto A^2$.

Intensity is maximum at points of constructive interference and zero at points of destructive interference.

Piazza Question

“What’s the difference between a sinusoidal wave and a standing wave?”

\[ y = Acos(kx - \omega t) \]

\[ y = [Asin(kx)]sin(\omega t) \]
On a string of length $L$ with fixed end points, $y(0, t) = 0$ and $y(L, t) = 0$.

Only oscillations with specific wavelengths are allowed.

- $m$ is called the mode number.
- $m = 1$ is the “fundamental”.
- $m = 2$ is the “second harmonic”.

**i-Clicker Discussion Question**

What is the mode number of this standing wave?

A. 4.

B. 5.

C. 6.

D. Can’t say without knowing what kind of wave it is.
Standing Waves on a String

There are three things to note about the normal modes of a string.

1. $m$ is the number of antinodes on the standing wave.
2. The fundamental mode, with $m = 1$, has $\lambda_1 = 2L$.
3. The frequencies of the normal modes form a series: $f_1$, $2f_1$, $3f_1$, … These are also called harmonics. $2f_1$ is the “second harmonic”, $3f_1$ is the “third harmonic”, etc.

Musical Instruments

- Instruments such as the harp, the piano, and the violin have strings fixed at the ends and tightened to create tension.
- A disturbance generated on the string by plucking, striking, or bowing it creates a standing wave on the string.
- The fundamental frequency is the musical note you hear when the string is sounded:

$$f_1 = \frac{v}{2L} = \frac{1}{2L} \sqrt{\frac{F}{\mu}}$$

where $F$ is the tension in the string and $\mu$ is its linear density.
Before Class 24 on Wednesday

- Problem Set 10 on Sections 13.3-13.7 and 14.1-14.4 is due tomorrow by 11:59pm.
- If you haven’t done it, please check your utoronto email, respond to the course_evaluations email and evaluate me!
- We are skipping section 14.8 on Doppler Shift for this course.
- On Wednesday we will finish up to section 14.7, then I will do some course review and give some advice about the final exam.
- I also will be giving an “Exam Jam” lecture on Thursday from 10:00-11:30 in SS2135. I have posted a hand-out for Exam Jam on the portal page under “Extra Study Materials”, and I will post any written notes from Exam Jam on the portal after Thursday.