EVERY WAVE, REGARDLESS OF HOW HIGH AND FORCEFUL IT CRESTS, MUST EVENTUALLY COLLAPSE WITHIN ITSELF.

- STEFAN ZWEIG
What’s a Wave?

- A wave is a wiggle in time and space
- The source of a wave is almost always a vibration
  - A vibration is a wiggle in time
- So a wave is basically a traveling vibration
  - BUT carries energy from the vibrating source to the receiver; it does NOT transfer matter
The biggest earthquake in recorded history happened in Chile in 1960. It measured 9.5 in the Richter scale.

What if a magnitude 15 hit America? 20? 25?
Qualities of a Wave

- **Period** \((T)\)
  - Time it takes for one back-and-forth cycle
  - In seconds \((s)\)

- **Wavelength** \((\lambda)\)
  - Distance between successive identical parts of the wave
  - In meters \((m)\)

- **Frequency** \((f)\)
  - Number of vibrations in a given time
  - In Hertz \((Hz)\)

\[
f = \frac{1}{T}
\]
Qualities of a Wave

- **Velocity**
  - Speed and direction of the wave
  - In m/s
  - $v = \lambda f$

- **Crests**
  - Peaks or high point of the wave

- **Troughs**
  - Valleys or low points of the wave

- **Amplitude (A)**
  - Distance from midpoint to crest (or trough)
  - Maximum displacement from equilibrium
QUALITIES OF A WAVE

WAVE MOTION
Wave Speed

- In a freight train, each car is 10 m long. If two cars roll by you every second, how fast is the train moving?
  \[ v = \frac{d}{t} = 2 \times (10 \text{ m})/(1 \text{ s}) = 20 \text{ m/s} \]

- A wave has a wavelength of 10 m. If the frequency is 2 Hz, how fast is the wave traveling?
  \[ v = \lambda f = (10 \text{ m})(2 \text{ Hz}) = 20 \text{ m/s} \]
**Wave Speed**

- **Speed of a light wave**
  - $c = 299,792 \text{ km/s (186,282 mi/s)}$

- **Speed of sound (in dry air at 20° C)**
  - $v = 343.59 \text{ m/s (768.59 mph)}$

- **Speed of sound in a vacuum?**
  - $v = 0 \text{ m/s}$
Types of Waves

- **Transverse Waves**
  - Motion of the medium is perpendicular to the direction in which the wave travels
  - Examples:
    - Ripples in the water
    - A whip
    - Light
    - Earthquake secondary waves
Types of Waves

* Longitudinal Waves
  * Motion of the medium is in the same direction as in which the wave travels
  * Also called *compression waves*

* Examples:
  * Earthquake primary waves
  * Sound
Longitudinal Wave

Transverse Wave

Direction of Propagation

Particle Motion

Longitudinal Wave

Particle Motion
Timing and strength of seismic waves gives us a picture of the interior.
Interference

- Occurs when two or more waves meet
- Parts of the waves may overlap and form an *interference pattern*
- Wave effects may be increased, decreased, or neutralized
Interference

- When the crest of one wave overlaps with the crest of another, their individual effects add up
  - Called *constructive interference*
- When the crest of one wave meets the trough of another, their individual effects decrease
  - Called *destructive interference*
- Characteristic of *all* wave motion, whether water waves, sound waves, or light waves
Two waves in phase (Constructive Interference)

Two waves out of phase (Destructive Interference)

Wave 1

Wave 2

Combined Wave
Phase

- Phase is the relationship between the period of a wave and an external reference point.
- Two waves which are *in phase* are in synch.
- Two waves which are *out of phase* are out of synch.
Interferometry

- A family of techniques in which you use wave interference patterns to extract information about the wave is called interferometry.

- Usually measures interference between light waves (especially from lasers).
Interferometry

- Laser
- Half-silvered mirror
- Mirror
- Detector
Interferometry
Interference

Signal 1

Signal 2

Recombined
GRAVITATIONAL WAVES
FROM TWO ORBITING BLACK HOLES
GRAVITATIONAL WAVES & INTERFEROMETRY

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Standing Waves

- Also known as a *stationary wave*
- A **standing wave** is one where particular points on the wave are “fixed,” or stationary
  - Fixed points on a standing wave are called *nodes*
  - Positions on a standing wave with the largest amplitudes are called *antinodes*
- Antinodes occur halfway between nodes
Standing Waves

Nodes

Antinodes
Standing Waves

- Standing waves are the result of interference
- Two waves of equal amplitude and wavelength pass through each other in opposite directions
- Waves are always out of phase at the nodes
- Nodes are stable regions of destructive interference
ACOUSTIC LEVITATION

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2D STANDING WAVES

HTTPS://WWW.YOUTUBE.COM/WATCH?V=WVJAGRUBF4W
Electron Orbitals

- Electrons move around the nucleus in orbital shells. But why do the shells have electron-holding capacities of 2, 8, 18, 32… specifically?
- Electrons are both particles and waves
- Electrons bound to the nucleus are 3-dimensional standing waves!
Simple Harmonic Motion

- Oscillatory motion under a restoring force proportional to the amount of displacement from equilibrium

- A restoring force is a force that tries to move the system back to equilibrium
Describing Oscillation

- Begin with the origin at equilibrium
- $x$ is then the displacement from equilibrium, i.e. the change in the length of the spring
- When displaced, the spring force tends to restore the mass to equilibrium — *restoring force*
- Oscillation can only occur when there is a restoring force
Describing Oscillation

- Displace the body to the right to $x = A$ and let go.
- Net force and acceleration are to the **left**.
- Reaches maximum velocity at **O**.
- Net force at O is **zero**.
- Overshoots and compresses spring.
- Net force and acceleration to **right**.
- Compresses until $x = -A$. 
Terms for Periodic Motion

- Amplitude (A) — magnitude of displacement from equilibrium
  - Total range of motion is 2A
- Period (T) — seconds per cycle; \( T = 1/f \)
- Frequency (f) — cycles per second; \( f = 1/T \)
- Angular frequency (\( \omega \)) — \( \omega = 2\pi f = 2\pi/T \)
  - essentially average angular speed
Simple Harmonic Motion

- Periodic motion where the restoring force is directly proportional to the displacement from equilibrium
- Typified by motion obeying Hooke’s Law
- Motion is sinusoidal
Hooke’s Law

- $F_s = -kx$
  - Restoring force exerted by an ideal spring
  - IMPORTANT ASSUMPTION: no friction and massless spring
- $a = F_s/m = -kx/m$
Things to Note

- $a = -\frac{kx}{m}$
- Acceleration is NOT constant
- Cannot use kinematic equations
Harmonic Oscillators

- Why are they important?
- SHM is a powerful model for many different periodic motions
- E.g. Electric current in an AC circuit, vibrations on a guitar string, vibrations of atoms in molecules
Imagine watching the shadow of a ball being swung in a vertical circle

If the amplitude of the body’s oscillation is equal to the radius of the sting attached to the ball

And if the angular frequency $2\pi f$ of the oscillating body is equal to the angular speed $\omega$ of the revolving ball

The motion of the shadow is identical to the motion of the ideal spring

http://www.animations.physics.unsw.edu.au/jw/SHM.htm
SHM and Circular Motion

- Acceleration of ball on string: $a = \omega^2 r$
- Acceleration of S-M system: $a = (k/m)x$
- $r = x$
- $\omega^2 = k/m$ or $\omega = \sqrt{(k/m)}$
SHM and Circular Motion

- \[ f = \frac{\omega}{2\pi} = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \]
- \[ T = \frac{2\pi}{\omega} = 2\pi \sqrt{\frac{m}{k}} \]

The larger the mass, the greater the moment of inertia, the longer it takes to complete a cycle.

The stiffer the spring (the larger \( k \)), the shorter the time \( T \) per cycle.
Things to Note

- Don’t confuse frequency $f$ with angular frequency $\omega = 2\pi f$
- The period and frequency do NOT depend on the amplitude $A$
- Bigger $A \rightarrow$ larger restoring force $\rightarrow$ higher average velocity
Example

- A 6.0 N weight is hung from a spring. The weight stretches the spring 0.030 m.
- Calculate the spring constant $k$

- $F_s = F_g$
- $-kx = -W$
- $k = W/x$
- $k = 200 \text{ N/m}$
Example

- The same spring is placed horizontally with one attached to the wall and the other attached to a 0.50 kg mass. The mass is pulled a distance of 0.020 m, released, and allowed to oscillate

- Find the angular frequency, frequency, and period of oscillation

  \[ \omega = \sqrt{\frac{k}{m}} = \sqrt{\frac{200}{0.50}} = 20 \text{ rad/s} \]

  \[ f = \frac{\omega}{2\pi} = 3.18 \text{ Hz} \]

  \[ T = \frac{1}{f} = 1/3.18 = 0.314 \text{ s} \]
SHM of a Simple Pendulum

- Almost exactly the same behavior as the mass-spring system

- Except:
  - The restoring force is the force of gravity
  - \[ T = 2\pi \sqrt{\frac{L}{g}} \]
  - Independent of \( A \) (same reason as M-S system)
  - Independent of \( m \) (guesses why?)
Displacement in SHM

\[ x(t) = A \cos(\omega t) \]

- Could have written in terms of sine since \( \cos \theta = \sin (\theta + \pi/2) \)
- In SHM the position is a periodic, sinusoidal function of time
Velocity and Acceleration in SHM

\[ v(t) = x' = -\omega A \sin(\omega t) \]

\[ v(x) = -\sqrt{\omega (A^2 - x^2)} \]

\[ a(t) = x'' = -\omega^2 A \cos(\omega t) \]

\[ v_{\text{max}} = A \omega \]
Energy in SHM

- $PE_s = \frac{1}{2}kx^2$
- $PE_g = mgh$
- $KE = \frac{1}{2}mv^2$
Question

A 17.0 g mass on a 35 N/m spring is pulled 20 cm from equilibrium and released. What is the position of the mass at time $t = 1.2$ s?
Answer

- $x = A \cos(\omega t)$
  - $\omega = \sqrt{k/m}$
  - $\omega = \sqrt{(35 \text{ N/m})/(0.017 \text{ kg})}$
  - $\omega = 45.4 \text{ rad/s}$
- $x = (0.2 \text{ m})\cos[(45.4 \text{ rad/s})(1.2 \text{ s})]$  
  - $x = -0.101 \text{ m or } -10.1 \text{ cm}$
Question

You find yourself on a strange planet armed only with a simple pendulum. The bob of the pendulum hangs on a 0.45 m long string and will swing through a full oscillation in 1.7 s once set in motion. Use this information to find the acceleration due to gravity on this foreign planet.