Conceptual Physics
Waves

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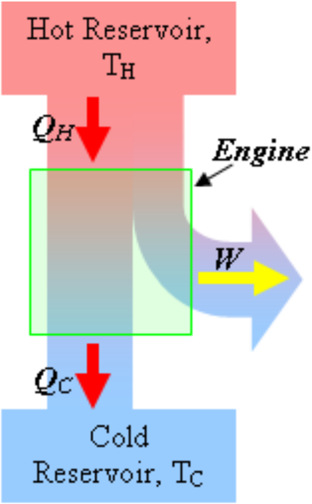
Last time

- phase changes
- laws of thermodynamics
- entropy
- heat engines

Overview

- heat engines
- vibrations and oscillations
- simple harmonic motion
- describing waves
- types of waves
- interference
- reflection
- standing waves

Heat Engines



[1]Diagram from http://www2.ignatius.edu/faculty/decarlo/

Efficiency of a Heat Engine

Efficiency:

$$e = \frac{Q_H - Q_C}{Q_H} = \frac{W}{Q_H}$$

An ideal engine, one that has the highest possible efficiency (a Carnot engine), has efficiency:

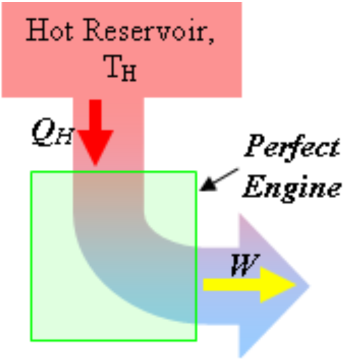
$$e = \frac{T_H - T_C}{T_H}$$

(T is measured in Kelvin!)

It is not possible for any engine to have efficiency higher than this without violating the 2nd law.

“Perfect” but Impossible Engine

It would be nice if all heat energy Q_H could be converted to work.



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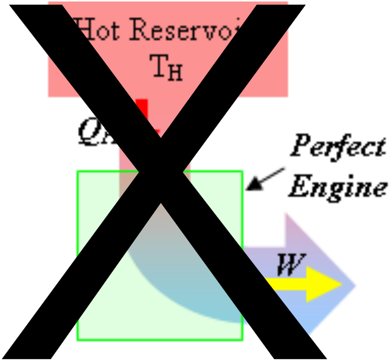


But this is not possible.

That would require $T_C = 0$, so that $W = Q_H$. Cannot happen.

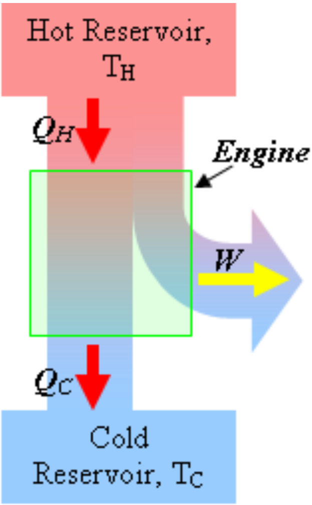
Second Law and Heat Engines

We can state the second law also as a fundamental limitation on heat engines.

Second Law of Thermodynamics (Heat Engine version)

It is impossible to construct a heat engine that, operating in a cycle, produces no effect other than the input of energy by heat from a reservoir and the performance of an equal amount of work.

Heat Engines



[1]Diagram from http://www2.ignatius.edu/faculty/decarlo/

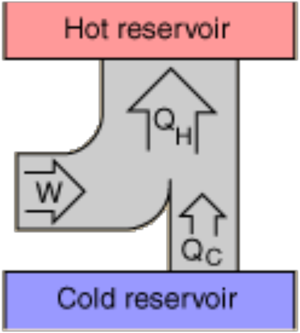
Heat Engine question

Problem 2, page 331.

Consider an ocean thermal energy conversion (OTEC) power plant that operates on a temperature difference between deep 4°C water and 25°C surface water. Show that the Carnot efficiency of this plant is 7%.

Heat Pump

Refrigerators work by taking electrical energy, converting it to work, then pumping heat from a cold area to a hotter one.



[1]Diagram from http://hyperphysics.phy-astr.gsu.edu

Question

Suppose you have a house with very excellent insulation. If you leave the door to your refrigerator open for the day, what happens to the temperature of your house?

(A) It increases.

(B) It decreases.

Question

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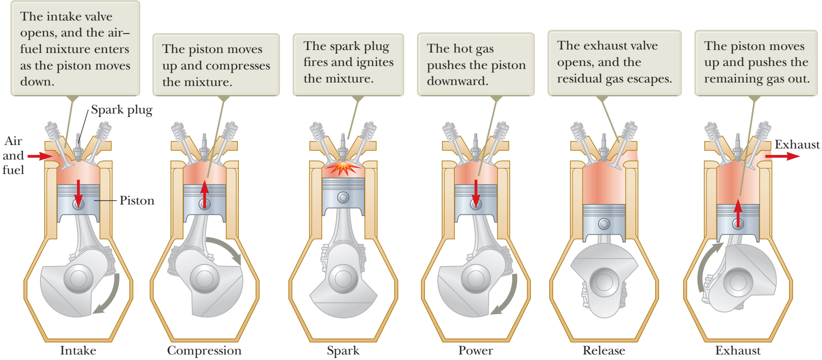
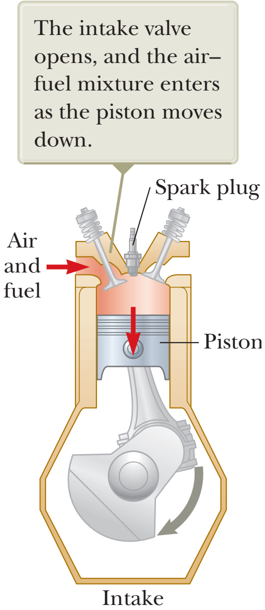
Car Engines

Car engines work by burning fuel in cylinders with pistons.

The four stroke cycle:

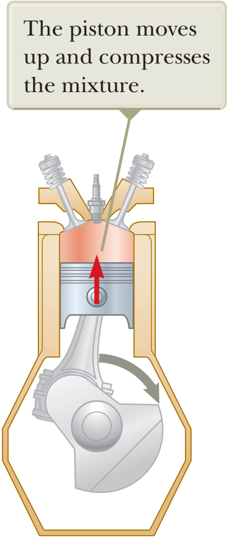


Car Engines



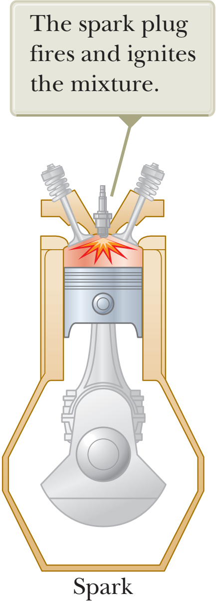
The intake valve opens, and the air–fuel mixture enters as the piston moves down.
Spark plug
Air and fuel
Piston
Intake

Car Engines

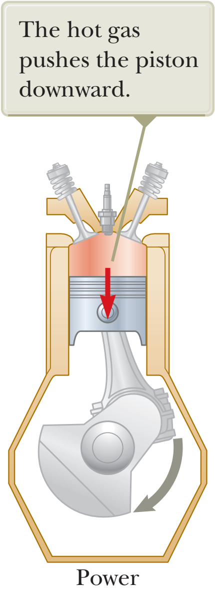


Compression

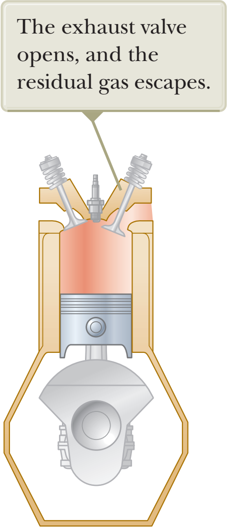
Car Engines



Car Engines

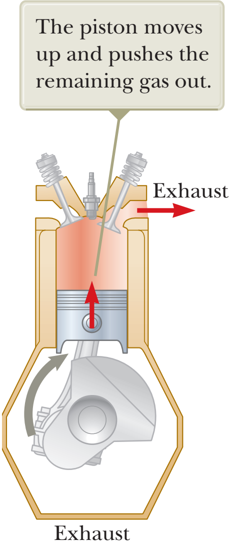


Car Engines



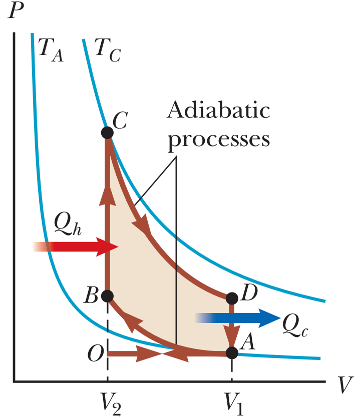
Release

Car Engines


The piston moves up and pushes the remaining gas out.
Exhaust
Exhaust

PV Diagrams and Adiabatic Processes

The 4-stroke cycle can be represented plotting pressure against volume of the gas in the cylinder.

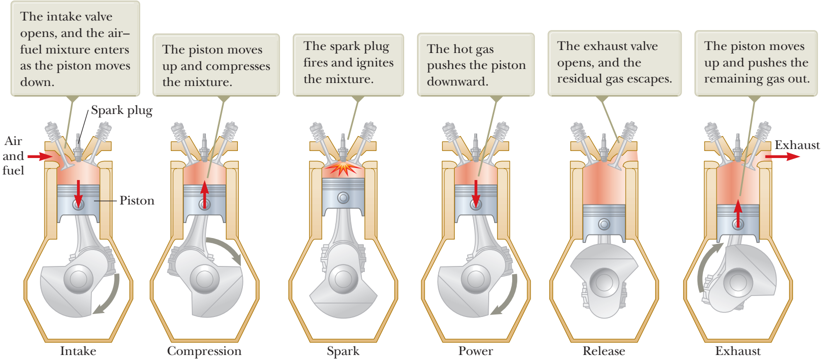


Adiabatic process

Process in which heat is not transferred into or out of the working fluid.

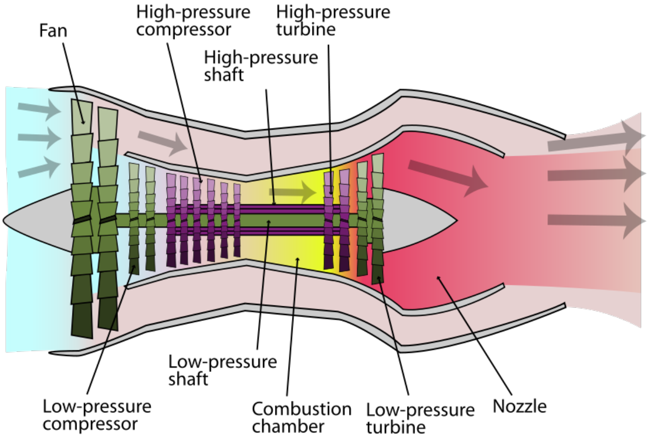
Car Engines

The four stroke cycle:



Jet Engines

Jet engines are even simpler and more efficient than car engines.

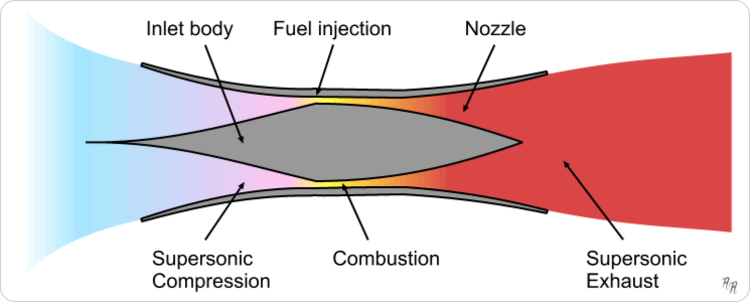


However, they require more advanced materials...

[1]Turbofan schematic from Wikipedia by K. Aainsqatsi.

Advanced Jets: Scramjet

...and higher speeds of operation.



[1]Scramjet schematic from Wikipedia by User:Emoscopes.

Oscillations and Periodic Motion

Many physical systems exhibit cycles of repetitive behavior.

After some time, they return to their initial configuration.

Examples:

- clocks
- rolling wheels
- pendulums
- bobs on springs

Oscillations

oscillation

motion that repeats over a period of time

amplitude

the magnitude of the vibration; how far does the object move from its average (equilibrium) position.

period, T

the time for one complete oscillation.

After 1 period, the motion repeats itself.

Measuring Oscillations

frequency

The number of complete oscillations in some amount of time. Usually, oscillations per second.

$$f = \frac{1}{T}$$

Units of frequency: Hertz. $1 \text{ Hz} = 1 \text{ s}^{-1}$

If one oscillation takes a quarter of a second (0.25 s), then there are 4 oscillations per second. The frequency is $4 \text{ s}^{-1} = 4 \text{ Hz}$.

Period and frequency question

Ch 18, problem 2

What is the period, in seconds, that corresponds to each of the following frequencies?

1. 10 Hz
2. 0.2 Hz
3. 60 Hz

[0] Hewitt, page 350.

Simple Harmonic Motion

The oscillations of bobs on springs and pendula is very regular and simple to describe.

It is called simple harmonic motion.

simple harmonic motion (SHM)

any motion in which the acceleration is proportional to the displacement from equilibrium, but opposite in direction

The force causing the acceleration is called the “restoring force”.

SHM and Springs

If a mass is attached to a spring, the force on the mass depends on its displacement from the spring's natural length.

Hooke's Law:

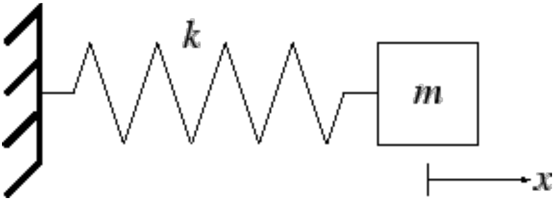
$$\mathbf{F} = -k\mathbf{x}$$

where k is the spring constant and x is the displacement (position) of the mass.

Hooke's law gives the force on the bob $\Rightarrow$ SHM.

The spring force is the *restoring force*.

SHM and Springs



Period, $T = 2\pi\sqrt{\frac{m}{k}}$

Only depends on the mass of the bob and the spring constant.
Does not depend on the amplitude.

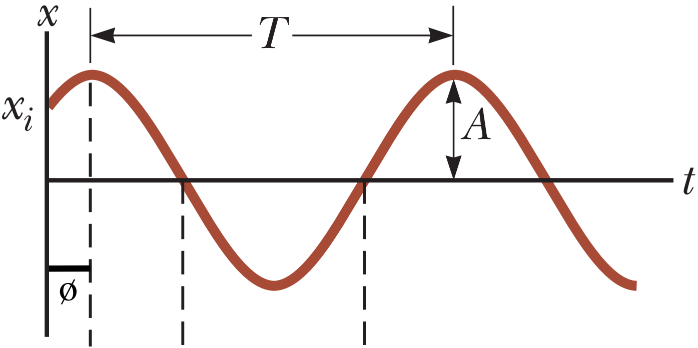
The position of the bob at a given time is given by:

$$x = A\cos\left(\sqrt{\frac{k}{m}}t + \phi\right)$$

Waveform

Location of the mass at a given time, t:

$$x = A\cos(\omega t + \phi)$$



$$f = \frac{1}{T}$$

[1] Figure from Serway & Jewett, 9th ed.

Question

Problem 4, page 350.

A weight suspended from spring is seen to bounce up and down over a distance of 20 cm twice each second. What is its frequency? Its period? Its amplitude?

Oscillations and Waveforms

Any oscillation can be plotted against time. *eg.* the position of a vibrating object against time.

The result is a *waveform*.

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Any oscillation can be plotted against time. *eg.* the position of a vibrating object against time.

The result is a *waveform*.

From this wave description of the motion, a lot of parameters can be specified.

This allows us to quantitatively compare one oscillation to another.

Examples of quantities: period, amplitude, frequency.

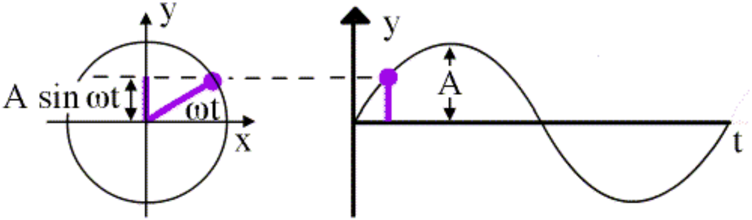
Oscillations

angular frequency

angular displacement per unit time in rotation, or the rate of change of the phase of a sinusoidal waveform

$$\omega = \frac{2\pi}{T} = 2\pi f$$

Circular Oscillations and Sine Waveforms



[1]Figure from School of Physics webpage, University of New South Wales.

SHM and Springs

$$x = A\cos(\omega t + \phi)$$

ω is the angular frequency of the oscillation.

When $t = \frac{2\pi}{\omega}$ the block has returned to the position it had at $t = 0$. That is one complete cycle.

SHM and Springs

$$x = A\cos(\omega t + \phi)$$

ω is the angular frequency of the oscillation.

When $t = \frac{2\pi}{\omega}$ the block has returned to the position it had at $t = 0$. That is one complete cycle.

Recalling that $\omega = \sqrt{k/m}$:

$$\text{Period, } T = 2\pi\sqrt{\frac{m}{k}}$$

Only depends on the mass of the bob and the spring constant.
Does not depend on the amplitude.

SHM and Springs Question

If the mass of the bob is quadrupled (and everything else is unchanged), what happens to the period of the motion?

If the spring constant is halved (and everything else is unchanged), what happens to the period of the motion?

Pendula and SHM

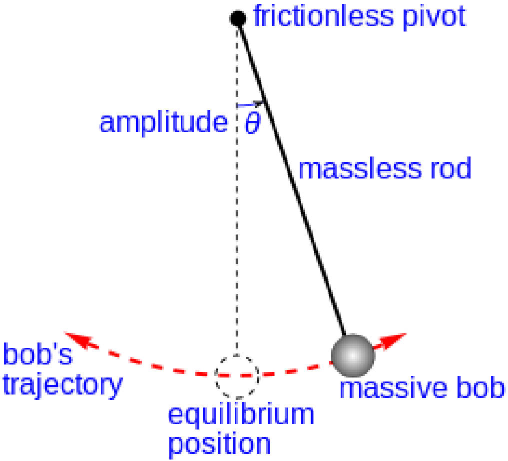
pendulum

a massive bob attached to the end rod or string that will oscillate along a circular arc under the influence of gravity

A pendulum bob that is displaced to one side by a small amount and released follows SHM to a good approximation.

Gravity and the tension in the string provide the *restoring force*.

Pendula and SHM



$$\text{Period} = 2\pi\sqrt{\frac{L}{g}}$$

Pendula and SHM

The net force on the pendulum bob is $-mg\sin\theta$, when the string is at an angle θ to the vertical.

For small values of θ, $\sin\theta \approx \theta$.

That means for small oscillations of a pendulum, the restoring force on the bob is roughly:

$$F = -mg\theta$$

and the motion is SHM.

Pendula and SHM

Here, $\omega = \sqrt{\frac{g}{L}}$.

At a given time t the angle the pendulum bob makes with the vertical is

$$\theta = \theta_{max} \cos(\omega t + \phi)$$

where θ_{max} is the amplitude and $T = \frac{2\pi}{\omega}$ is the period.

Period, $T = 2\pi \sqrt{\frac{L}{g}}$

Problem

Problem 8, page 350.

An astronaut on the Moon attaches a small brass ball to a 1.00 m length of string and makes a simple pendulum. She times 15 complete swings in a time of 75 seconds. From this measurement she calculates the acceleration due to gravity on the Moon. What is her result?

Problem

Problem 8, page 350.

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$1.58\ m/s^2$

Waves

Very often an oscillation or one-time disturbance can be detected far away.

Plucking one end of a stretched string will eventually result in the far end of the string vibrating.

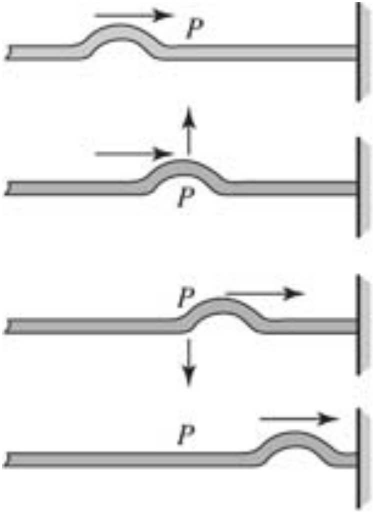
The string is a medium along which the vibration travels.

It carries energy from on part of the string to another.

Wave

a disturbance or oscillation that transfers energy through matter or space.

Wave pulses



Kinds of Waves

medium

a material substance that carries waves. The constituent particles are temporarily displaced as the wave passes, but they return to their original position.

Kinds of waves:

- mechanical waves – waves that travel on a medium, *eg.* sound waves, waves on string, water waves
- electromagnetic waves – light, in all its various wavelengths, *eg.* x-rays, uv, infrared, radio waves
- matter waves – (particles are also wavelike...)

Waves

If the source of the disturbance continues to oscillate, in can create regular waves that travel outward.

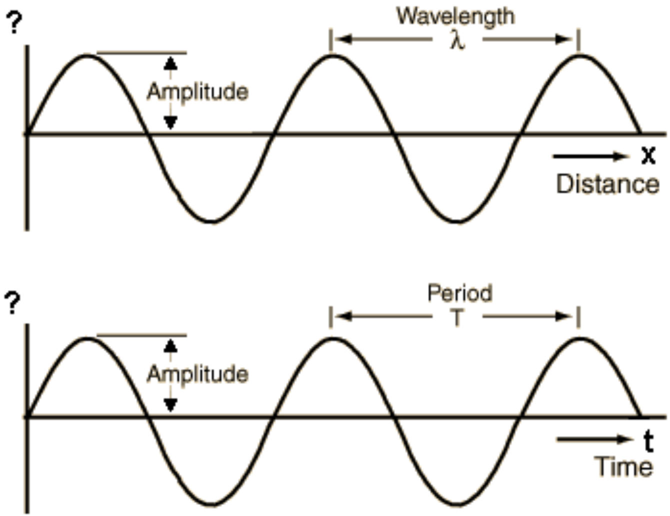
The cycles not only have a frequency, but also take up some amount of physical space.

The distance from the start of one cycle to the start of the next is the *wavelength*.

wavelength

the length of a single complete wave cycle

Wave Quantities



Wave speed

How fast does a wave travel?

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

It travels the distance of one complete cycle in the time for one complete cycle.

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

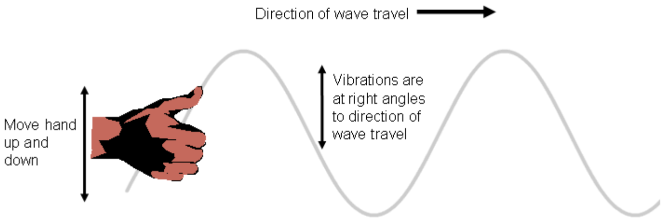
But since frequency is the inverse of the time period, we can relate speed to frequency and wavelength:

$$v = f\lambda$$

Transverse Waves

Transverse wave

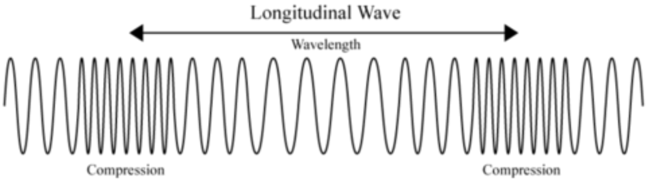
a wave with the oscillation in a direction **perpendicular** to the direction of propagation



Longitudinal Waves

Longitudinal wave

a wave with the oscillation in a direction **parallel** to the direction of propagation



Transverse vs. Longitudinal

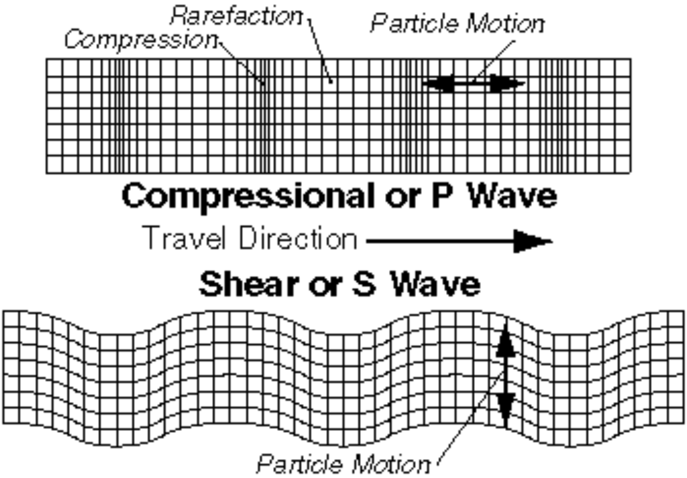
Examples of transverse waves:

- vibrations on a guitar string
- ripples in water
- light
- S-waves in an earthquake (more destructive)

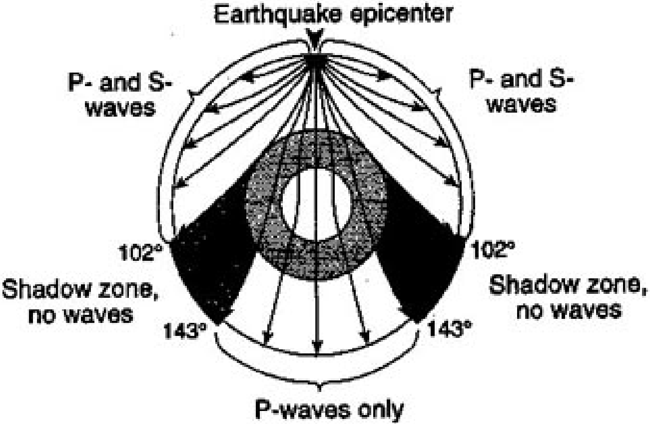
Examples of longitudinal waves:

- sound
- P-waves in an earthquake (initial shockwave, faster moving)

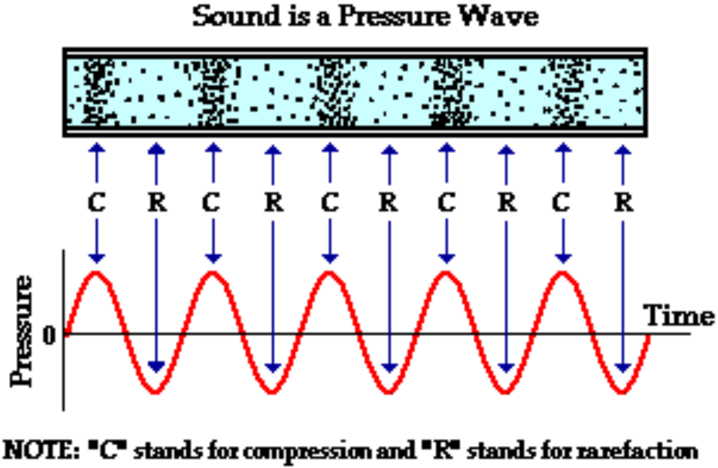
Earthquakes



Earthquakes



Sound waves

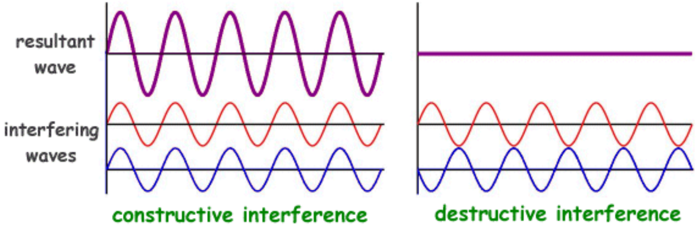


Sound is a Pressure Wave
C
R
C
R
C
R
C
R
C
R
Pressure
0
Time
NOTE: "C" stands for compression and "R" stands for rarefaction

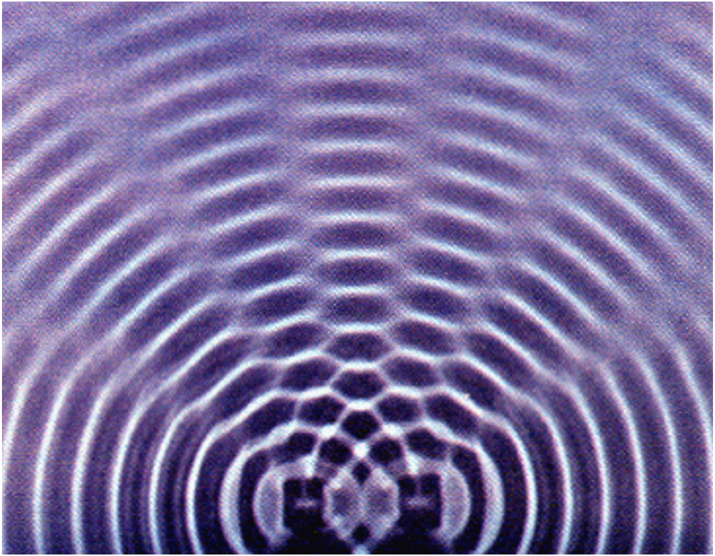
Interference of Waves

When two wave disturbances interact with one another they can amplify or cancel out.

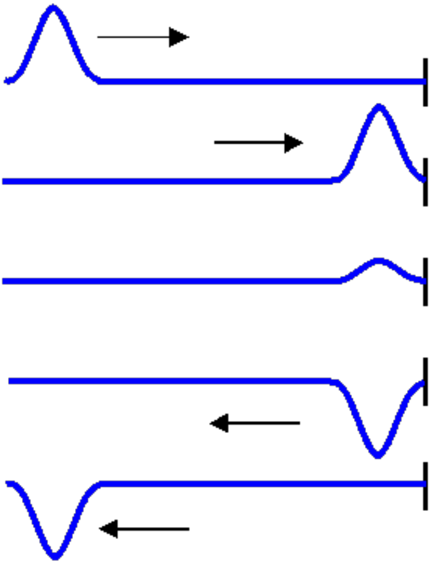
Waves of the same frequency that are "in phase" will reinforce, amplitude will increase; waves that are "out of phase" will cancel out.



Interference of Waves

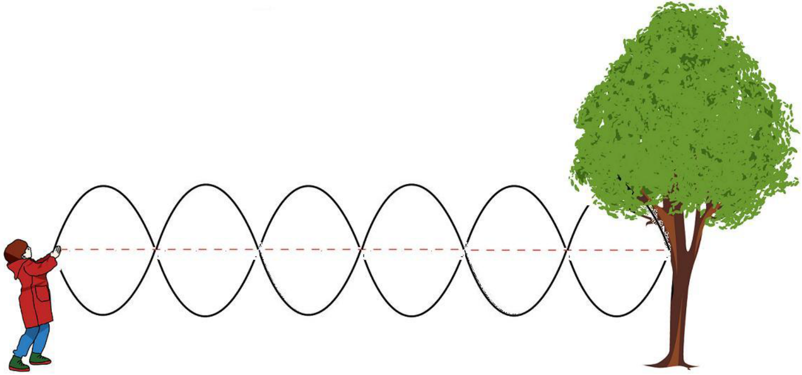


Wave Reflection



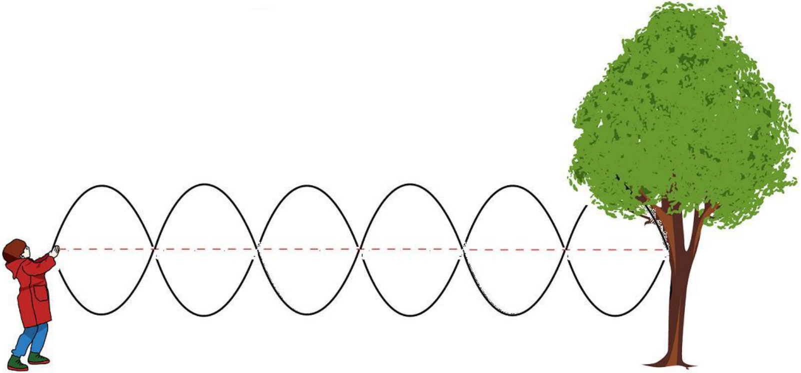
Standing Waves

It is possible to create waves that do not seem to propagate.



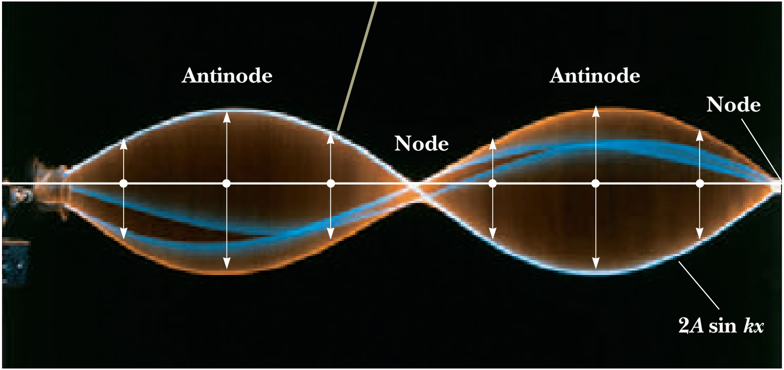
They are produced by a wave moving to the left interfering with the wave reflected back the right.

Standing Waves



Notice that there are a whole number of half wavelengths between the child and the tree.

Nodes and Antinodes



Summary

- engines
- vibrations and oscillations
- simple harmonic motion
- types of waves
- interference

Homework

- Waves worksheet. (due Mon, Aug 7th)
- Prepare a 5-8 minute talk for next week. Tuesday, Aug 8.
- Essay question (Due Thurs, Aug 3rd)
- Hewitt, Ch 19, onward from page 347. Exercises: 1, 11; Problems: 1, 3, 5