Waves
Doppler Effect
Bow and Shock Waves

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Last time

- power of a sound wave
- sound level & perception of sound with frequency
- the Doppler effect

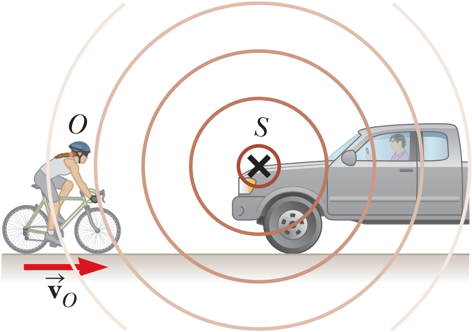
Overview

- the Doppler effect
- bow and shock waves

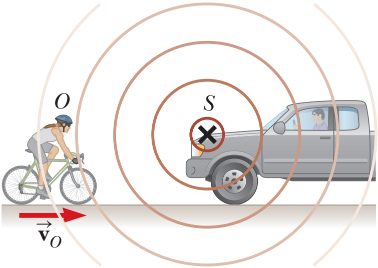
Reminder: The Doppler Effect

The frequency of a sound counts how many wavefronts (pressure peaks) arrive per second.

If you are moving towards a source of sound, you encounter more wavefronts per second $\rightarrow$ the frequency you detect is higher!



The Doppler Effect



The speed you see the waves traveling relative to you is $v' = v + v_o$, while relative to the source the speed is v.

$$f' = \frac{v'}{\lambda} = \left(\frac{v + v_o}{v}\right) f$$

(v and v_o are positive numbers.)

The Doppler Effect

The speed you see the waves traveling relative to you is $v' = v + v_0$, while relative to the source the speed is v.

$$f' = \frac{v'}{\lambda} = \left(\frac{v + v_o}{v}\right) f$$

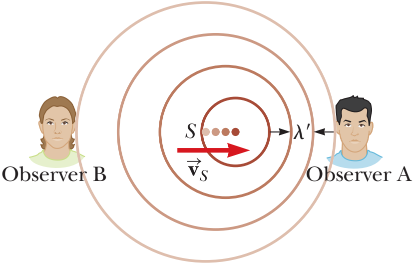
(v and v_o are positive numbers.)

Moving *away* from the source, the relative velocity of the detector to the source decreases $v' = v - v_o$.

$$f' = \left(\frac{v - v_o}{v}\right) f$$

The Doppler Effect

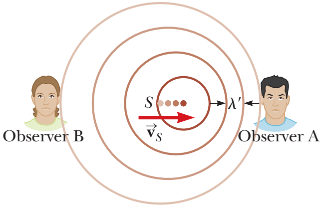
A similar thing happens if the *source* of the waves is moving.



In the diagram, the source is moving toward the wavefronts it has created on the right and away from the wavefronts it has created on the left.

This changes the wavelength of the waves around the source. They are shorter on the right, and longer on the left.

The Doppler Effect

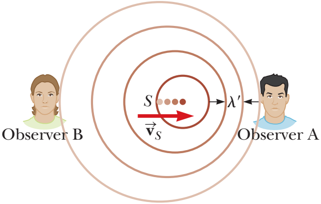


Observer A detects the wavelength as $\lambda' = \lambda - v_s T = \lambda - \frac{v_s}{f}$.

For A:

$$f' = \frac{v}{\lambda'} = \left(\frac{v}{v/f - v_s/f}\right) = \left(\frac{v}{v - v_s}\right) f$$

The Doppler Effect



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For Observer B:

$$f' = \left(\frac{v}{v + v_s}\right) f$$

The Doppler Effect

In general:

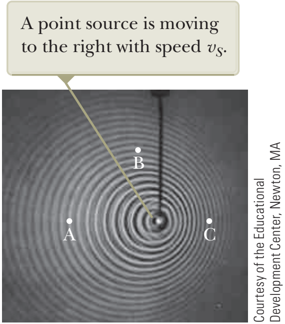
$$f' = \left(\frac{v \pm v_o}{v \mp v_s} \right) f$$

The top sign in the numerator and denominator corresponds to the detector and/or source moving *towards* on another.

The bottom signs correspond to the detector and/or source moving *away from* on another.

The Doppler Effect

Quick Quiz 17.4[1] Consider detectors of water waves at three locations A, B, and C in the picture. Which of the following statements is true?



(A) The wave speed is highest at location C.

(B) The detected wavelength is largest at location C.

(C) The detected frequency is highest at location C.

(D) The detected frequency is highest at location A.

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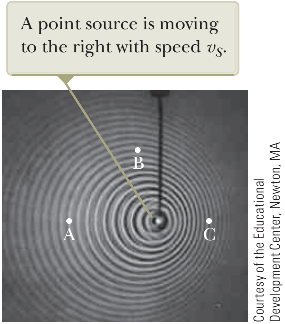
[1] Serway & Jewett, page 520.

The Doppler Effect

Quick Quiz 17.4[1] Consider detectors of water waves at three locations A, B, and C in the picture. Which of the following statements is true?



(A) The wave speed is highest at location C.

(B) The detected wavelength is largest at location C.

(C) The detected frequency is highest at location C. ←

(D) The detected frequency is highest at location A.

[1] Serway & Jewett, page 520.

The Doppler Effect Question

A police car has a siren tone with a frequency at 2.0 kHz.

It is approaching you at 28 m/s. What frequency do you hear the siren tone as?

Now it has passed by and is moving away from you. What frequency do you hear the siren tone as now?

The Doppler Effect Question

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approaching: 2.2 kHz
receding (moving away): 1.8 kHz

The Doppler Effect for Light

Electromagnetic radiation also exhibits the Doppler effect, however, the equation needed to describe the effect is different.

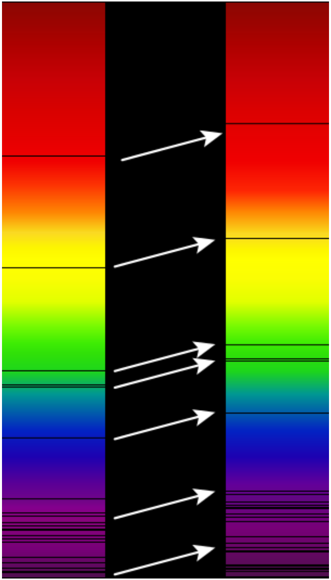
For em radiation:

$$f' = \frac{\sqrt{1 + v/c}}{\sqrt{1 - v/c}} f$$

Relativity is needed to derive this expression (hold on for Phys4D).

This can be used to determine how fast distant objects in space are moving toward or away from us.

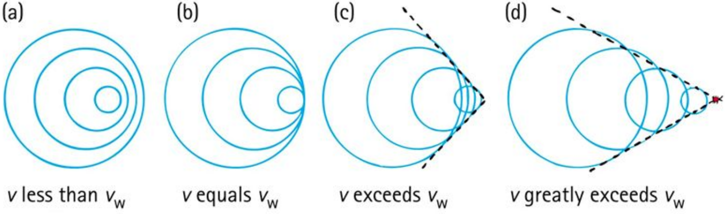
The Doppler Effect and Astronomy



[1] Image from Wikipedia by Georg Wiora.

Bow Waves and Shock Waves

Bow waves and shock waves can be detected by nearby observers when the speed of the wave source exceeds the speed of the waves.



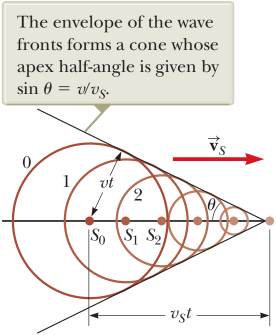
This effect happens when an aircraft transitions from subsonic flight to supersonic flight.

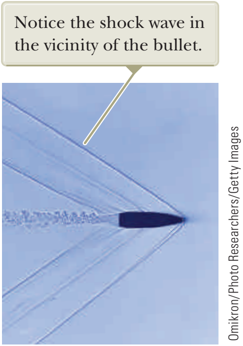
[1] Figure from Hewitt, 11ed.

Bow waves

Supersonic transition

Shock Waves





The angle which the shockwave makes is called the **Mach angle**.

$$\sin \theta = \frac{v}{v_s}$$

The ratio v_s/v is called the **Mach number**.

Shock Waves Question

Quick Quiz 17.6[2] An airplane flying with a constant velocity moves from a cold air mass into a warm air mass. What happens to the Mach number?

(A) it increases

(B) it decreases

(C) it stays the same

[2]Serway & Jewett, page 522.

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Hint:

$$v = 331\sqrt{1 + \frac{T_{\text{Cel}}}{273}} \text{ [m/s]}$$

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[2]Serway & Jewett, page 522.

Shock Waves Question

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[2] Serway & Jewett, page 522.

Waves

Any questions about waves?

Light

We are now moving on to chapters 35-38.

Light is also a wave.

What is Light?

Physicists have long been interested in the nature and uses of light.

Egyptians and Mesopotamians developed lenses. Later Greeks and Indians began to develop a theory of geometric optics

Geometric optics was greatly advanced in 800-1000 by Arab philosophers, especially Ibn al-Haytham (called Alhazen).

Newton developed a particle model of light, which explained reflection and refraction.

Christian Huygens proposed a wave model of light (1678) and pointed out that it could also explain reflection and refraction, but it was less popular.

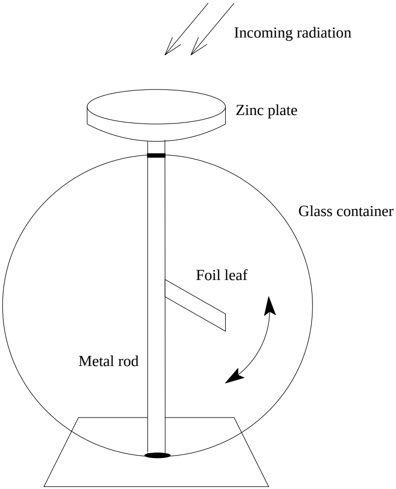
What is Light?

Thomas Young experimentally demonstrated the interference of light, which confirmed that it needed to be considered as being wave-like.

This fit with the understanding of Maxwell's equations.

Hertz then discovered the **Photoelectric effect** and was unable to explain it with a wave model of light.

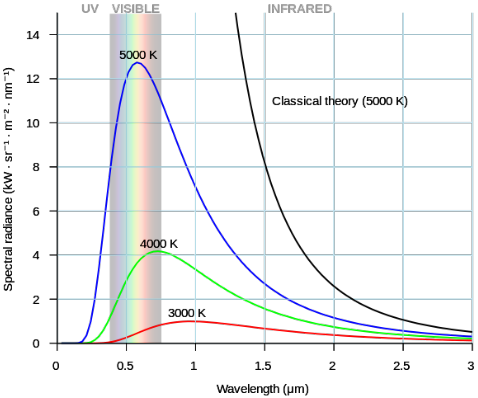
Photoelectric Effect



Even very intense light at a low frequency will not allow the plate to discharge. As soon as just a little light at a high frequency falls on the plate it begins discharging.

What is Light?

Recall the blackbody radiation distribution of wavelengths.



Classical theory, with light as a wave, could not explain the shape of the distribution.

Max Planck suggested a model that imagined light energy came in discrete units.

[1] Graph from Wikipedia, created by user Darth Kule.

What is Light?

Einstein resolved the issue of the photoelectric effect by taking literally Planck's quantization model and showing that light behaves like a wave, but also like a particle.

The "particles" of light are called **photons**.

The energy of a photon depends on its frequency:

$$E = hf$$

where $h = 6.63 \times 10^{-34}$ J s is **Planck's constant**.

Speed of Light

Light travels very fast.

We can figure out how fast it goes from Maxwell's laws, by deriving a wave equation from them. (Skipping! See Ch 34 for a proof.)

Maxwell's Equations

$$\oint \mathbf{E} \cdot d\mathbf{A} = \frac{q_{enc}}{\epsilon_0}$$

$$\oint \mathbf{B} \cdot d\mathbf{A} = 0$$

$$\oint \mathbf{E} \cdot d\mathbf{s} = -\frac{d\Phi_B}{dt}$$

$$\oint \mathbf{B} \cdot d\mathbf{s} = \mu_0 \epsilon_0 \frac{d\Phi_E}{dt} + \mu_0 I_{enc}$$

In free space (a vacuum) with no charges $q_{enc} = 0$ and $I_{enc} = 0$.

[1]Strictly, these are Maxwell's equations in a vacuum.

Maxwell's Equations Differential Form

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \mu_0 \mathbf{J}$$

In free space with no charges $\rho = 0$ and $\mathbf{J} = 0$.

Maxwell's Equations and the Wave Equation

By taking a derivative and plugging Maxwell's equations into one another:

$$\frac{\partial^2 E}{\partial x^2} = \mu_0 \epsilon_0 \frac{\partial^2 E}{\partial t^2}$$

The wave equation!

Another Implication of Maxwell's Equations

For a wave propogating in x direction:

$$\frac{\partial^2 E}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 E}{\partial \mathrm{t}^2}$$

The constant c appears as the wave speed and

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$$

$c = 3.00 \times 10^8$ m/s, is the speed of light.

The values of ϵ_0 and μ_0 together predict the speed of light!

$\epsilon_0 = 8.85 \times 10^{-12}$ $\mathrm{C^2\,N^{-1}m^{-2}}$ and $\mu_0 = 4\pi \times 10^{-7}$ kg m $\mathrm{C^{-2}}$

Another Implication of Maxwell's Equations

The same process gives the same wave equation for the magnetic field: $\frac{\partial^2 B}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 B}{\partial t^2}$

Wave solutions:

$$\begin{aligned} \mathbf{E} &= \mathbf{E_0} \sin(kx - \omega t) \\ \mathbf{B} &= \mathbf{B_0} \sin(kx - \omega t) \end{aligned}$$

where $c = \frac{\omega}{k}$.

These two solutions are in phase. There is no offset in the angles inside the sine functions.

The two fields peak at the same point in space and time.

At all times:

$$\frac{E}{B} = c$$

Maxwell's Equations and the Wave Equation

Wave solutions for the wave equation in for E and B:

$$\mathbf{E} = \mathbf{E_0} \sin(kx - \omega t)$$
$$\mathbf{B} = \mathbf{B_0} \sin(kx - \omega t)$$

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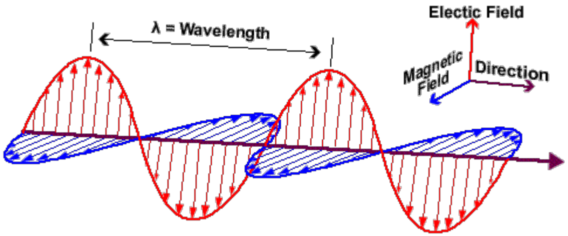

Summary

- the Doppler effect
- bow and shock waves
- light as a wave

5th Test Tuesday, June 9.

Waves Quiz anytime today, finish by 11:58pm.

Homework Serway & Jewett (suggested):

- Ch 17, onward from page 523. Probs: 54, 71