Sections 16.8, 16.9, 32.1 to 32.5

We now consider the **Doppler effect** for sound (simplified to one dimension, no wind, and a source emitting a sound of single frequency f_S): When a source S and a listener L have a non-zero relative speed, the listener hears a higher frequency ($f_L > f_S$) if L and S are moving closer together or a lower frequency ($f_L < f_S$) if L and S are moving apart. The frequencies f_L and f_S are both in Hz.

Note that *when the relative speed is zero*, $f_L = f_S$.

In order to write just one equation for the nine possibilities, **we choose the direction from listener to source as positive**. Equation (16.27) and its use in Example 16.14b are wrong because the minus signs in the *algebraic* equations should be plus signs. However, v_S itself is negative for all "in front" cases, so the numerator in the Example 16.14b's first numerical solution is 340 m/s + (–30 m/s).

The other equations are correct, including $\boxed{f_L = \frac{v + v_L}{v + v_S} f_S}$, where f_L, f_S, and v (the speed of sound) are always positive. All three v's must have the same unit ($\frac{\text{m}}{\text{s}}$ in SI). In this equation, v_L is the velocity *component* of the listener and v_S is the velocity *component* of the source. (The word "component" is often left out in the text.) **A velocity component is positive when the velocity direction is the same as the listener to source direction. A velocity component is negative when the velocity direction is opposite the listener to source direction.**

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Realizing that "velocity" should be "velocity component" and "velocities" should be "velocity components", cover up the solutions and carefully work Examples 16.15 to 16.18. (The driver of the police car has *zero* speed relative to the siren, so that driver hears 300 Hz directly from the siren in all four examples.)

If the source is moving faster than the speed of sound (that is, if $|v_S| > v$), that *supersonic* source produces a large-amplitude wave crest—a **shock wave** (or shock waves—see Fig. 16.35c and its caption). When $|v_S|$ and v are constant and the source is moving in a straight line, this three-dimensional shock wave is cone shaped. This shock-wave cone makes an angle α with the straight-line path of the supersonic source.

Our text derives an equation we change to $\boxed{\sin\alpha = \frac{v}{|v_S|}}$, where both the speed of sound v and the speed of the supersonic source $|v_S|$ are positive and have the same unit ($\frac{\text{m}}{\text{s}}$ in SI).

The **Mach number** is $\frac{|v_S|}{v}$, the *reciprocal* of the right side of this equation. Thus $\sin\alpha = \frac{1}{\text{the Mach number}}$. Changing all "v_S" to "$|v_S|$", cover up the solution and carefully work Example 16.19.

In Chapter 32, we begin adding our electromagnetism concepts to our wave concepts to describe sinusoidal *electromagnetic waves*. Electric fields and magnetic fields "wave" (that is, oscillate in space and time) in an **electromagnetic wave**, often called an **em wave**.

Maxwell's equations tell us that accelerated charges produce electromagnetic waves.

Figure 32.4 illustrates the **electromagnetic spectrum**. In order of increasing frequency (that is, decreasing wavelength), the electromagnetic spectrum has bands of *radio waves*, *microwaves*, *infrared*, *visible light* [λ_0 = 700 nm (red) to λ_0 = 400 nm (violet)], *ultraviolet*, *x rays*, and *gamma rays*.

In a **plane wave**, the oscillations all have the same phase in any geometric plane that is perpendicular to the wave's velocity.

An em wave has the property of **polarization**—that is, the direction of its electric field $\vec{E}$ is *not* arbitrary. (This "polarization" is *not* the electric dipole moment per volume vector of Block 4.) Specifically, in a **linearly-polarized em wave**, all electric fields $\vec{E}$ oscillate parallel to the same line and all magnetic fields $\vec{B}$ oscillate parallel to a perpendicular line. That is, $\vec{E}$ and $\vec{B}$ are perpendicular for this type of em wave.

Applying Maxwell's equations to an em wave in a dielectric gives $\boxed{E = \upsilon B}$, where E (in $\frac{\text{V}}{\text{m}}$ or $\frac{\text{N}}{\text{C}}$) is the magnitude of the em wave's electric field at some position and time and B (in T) is the magnitude of the em wave's magnetic field at the *same* position and the *same* time. In vacuum, $\upsilon \equiv c$. So, in vacuum, $E = \upsilon B$ becomes $\boxed{E = cB}$. The so-called "speed of light" c is defined to equal exactly 299,792,458 m/s: $c \approx 3.00 \times 10^8$ m/s.

In terms of the amplitudes of the two fields, E_{max} and B_{max}, two more special cases of $E = \upsilon B$ are $\boxed{E_{\text{max}} = \upsilon B_{\text{max}}}$ and $\boxed{E_{\text{max}} = cB_{\text{max}}}$.

Maxwell's equations also give $\boxed{\upsilon = \frac{1}{\sqrt{\varepsilon\mu}} = \frac{1}{\sqrt{KK_{\text{m}}}}\frac{1}{\sqrt{\varepsilon_0\mu_0}} = \frac{c}{\sqrt{KK_{\text{m}}}}}$ in a dielectric. In vacuum, $\varepsilon \equiv \varepsilon_0$, $\mu \equiv \mu_0$, $K = 1$, $K_{\text{m}} = 1$, and $\upsilon \equiv c$, so $\boxed{c = \frac{1}{\sqrt{\varepsilon_0\mu_0}}}$ is the special case included in the previous box. The values in air are approximately equal to those in vacuum.

In a dielectric, $\varepsilon = K\varepsilon_0$ and $\mu = K_{\text{m}}\mu_0$. Also, $K_{\text{m}} = 1$ and $\mu = \mu_0$ for nonmagnetic materials and $\mu \approx \mu_0$ and $K_{\text{m}} \approx 1$ near and above room temperature for diamagnetic and paramagnetic materials.
ε is the permittivity (in $\frac{\text{F}}{\text{m}}$) of the dielectric; ε_0 is the permittivity (in $\frac{\text{F}}{\text{m}}$) of vacuum ($\varepsilon_0 = 8.854 \times 10^{-12}\,\frac{\text{F}}{\text{m}}$).
μ is the permeability (in $\frac{\text{T·m}}{\text{A}}$) of the dielectric; μ_0 is the permeability (in $\frac{\text{T·m}}{\text{A}}$) of vacuum ($\mu_0 \equiv 4\pi \times 10^{-7}\,\frac{\text{T·m}}{\text{A}}$).
K is the dielectric constant (no unit) of the dielectric and K_{m} is its magnetic counterpart (no unit).

You should be able to use two of the boxed equations on the previous page to show that, for an em wave, the energy density of the magnetic field $u_B = \frac{B^2}{2\mu}$ equals the energy density of the electric field $u_E = \frac{1}{2}\varepsilon E^2$.

Cover up the solution and carefully work Example 32.2.

We now *define* the **Poynting vector** $\vec{S}$ by the vector equation $\boxed{\vec{S} \equiv \frac{1}{\mu}\vec{E} \times \vec{B}}$. Therefore, in the special case of vacuum (≈ air), $\boxed{\vec{S} = \frac{1}{\mu_0}\vec{E} \times \vec{B}}$. Note the magnitude of $\vec{E} \times \vec{B}$ is $EB \sin 90^\circ = EB$.

The magnitude of $\vec{S}$ is in $\frac{\mathrm{W}}{\mathrm{m}^2}$. **The direction of $\vec{S}$ is the direction of the em wave's velocity.** Thus the direction the wave is moving is the direction of $\vec{E} \times \vec{B}$, that is, perpendicular to *both* $\vec{E}$ and $\vec{B}$.

In Example 32.1, you should be able to find the magnetic field amplitude and use the right-hand rule with Fig. 32.15 to show the three perpendicular directions (of the two fields and of the wave velocity) are consistent.

For sinusoidal em waves, the intensity I is the average magnitude of the Poynting vector S_{av}, giving (in a dielectric) $\boxed{I = S_{av} = \frac{E_{max}B_{max}}{2\mu} = \frac{E_{max}^2}{2\mu v} = \frac{1}{2}\sqrt{\frac{\varepsilon}{\mu}}E_{max}^2 = \frac{1}{2}\varepsilon v E_{max}^2}$. In the special case of vacuum (≈ air), $\boxed{I = S_{av} = \frac{E_{max}B_{max}}{2\mu_0} = \frac{E_{max}^2}{2\mu_0 c} = \frac{1}{2}\sqrt{\frac{\varepsilon_0}{\mu_0}}E_{max}^2 = \frac{1}{2}\varepsilon_0 c E_{max}^2}$.

Recall the intensity I is the average power transmitted by the wave per perpendicular area and is thus in $\frac{\mathrm{W}}{\mathrm{m}^2}$.

Cover up the solution and carefully work Example 32.4.

The **radiation pressure** p_{rad} (in Pa = pascal) is the average pressure exerted by an em wave. For an em wave that hits normal (perpendicular) to a surface in vacuum (≈ air), $\boxed{p_{rad} = \frac{S_{av}}{c} = \frac{I}{c} \text{ for complete absorption}}$ and $\boxed{p_{rad} = \frac{2S_{av}}{c} = \frac{2I}{c} \text{ for complete reflection}}$. Recall that pressure is the perpendicular force per area.

Oppositely-directed em waves of the same amplitude, frequency, wavelength, and polarization add together to produce standing waves. For standing em waves between perfectly reflecting parallel walls a distance L (in m) apart, the allowed frequencies and wavelengths are f_n (in Hz) and λ_n (in m), similar to standing waves on a string … (fixed at both ends) and an open pipe. In a dielectric, $\boxed{f_n = \frac{v}{\lambda_n} = n\frac{v}{2L} \, (n = 1, 2, 3, 4, \ldots)}$. In the special case of vacuum (≈ air) between the walls, $v \equiv c$, so $\boxed{f_n = \frac{c}{\lambda_n} = n\frac{c}{2L} \, (n = 1, 2, 3, 4, \ldots)}$.

Try Example 32.7, realizing that Eq. (32.38) can be obtained from Eq. (32.39).