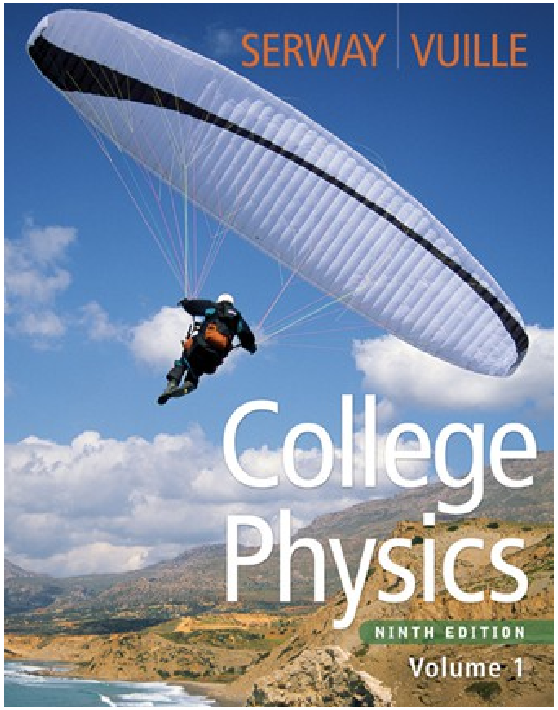

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Chapter 21

Alternating Current Circuits and Electromagnetic Waves

AC Circuits

- AC circuits power everyday electric appliances.
- Will look at various circuit elements in an AC circuit
  - Resistor
  - Capacitor
  - Inductor
- Also will look at what happens when these elements are placed in combinations in AC circuits

Electromagnetic Waves

- Electromagnetic waves are composed of fluctuating electric and magnetic fields.
- Electromagnetic waves come in various forms.

– These forms include

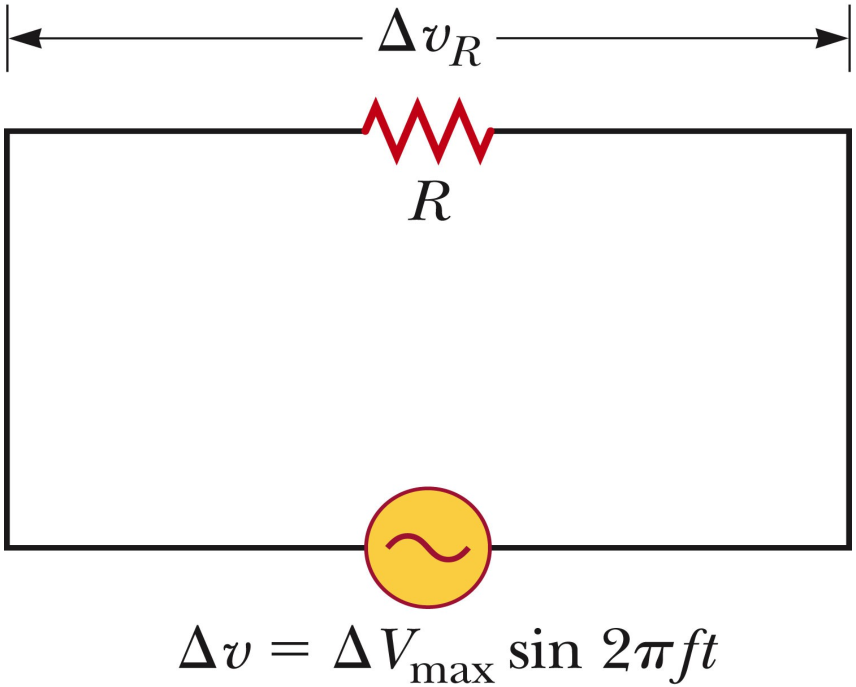
- Visible light
- Infrared
- Radio
- X-rays

AC Circuit

- An AC circuit consists of a combination of circuit elements and an AC generator or source.
- The output of an AC generator is sinusoidal and varies with time according to the following equation
  - $\Delta v = \Delta V_{max} \sin 2\geq \ f t$
- Δv is the instantaneous voltage
- ΔV_{max} is the maximum voltage of the generator
- f is the frequency at which the voltage changes, in Hz

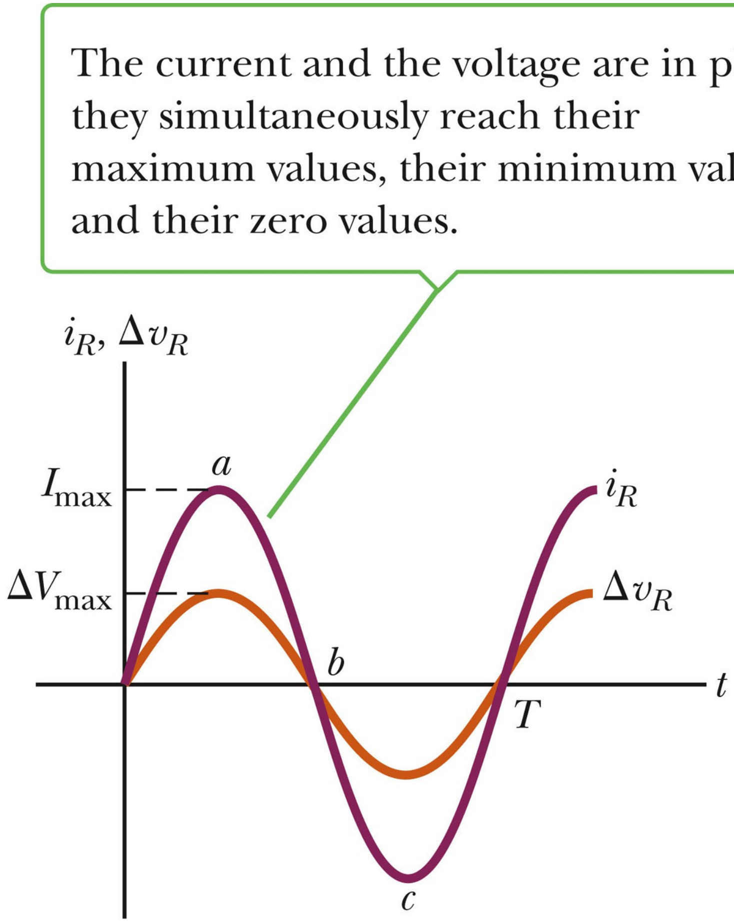
Resistor in an AC Circuit

- Consider a circuit consisting of an AC source and a resistor.
-



Resistor, Cont.

- The graph shows the current through and the voltage across the resistor.
- The current and the voltage reach their maximum values at the same time.
- The current and the voltage are said to be *in phase.*
-



More About Resistors in an AC Circuit

- The direction of the current has no effect on the behavior of the resistor.
- The rate at which electrical energy is dissipated in the circuit is given by
  - $P = i^2 R$
- Where i is the *instantaneous current*
- The heating effect produced by an AC current with a maximum value of I_{max} is not the same as that of a DC current of the same value.
- The maximum current occurs for a small amount of time.

rms Current and Voltage

- The *rms current* is the direct current that would dissipate the same amount of energy in a resistor as is actually dissipated by the AC current.

$$I_{rms} = \frac{I_{max}}{\sqrt{2}} = 0.707\, I_{max}$$

- Alternating voltages can also be discussed in terms of rms values.
-

$$\Delta V_{rms} = \frac{\Delta V_{max}}{\sqrt{2}} = 0.707\, \Delta V_{max}$$

$$i = I_{max} \sin 2\pi f t$$

$$\Delta V = \Delta V_{max} \sin 2\pi f t$$

$\therefore$ Average $\langle i \rangle = \langle I_{max} \sin 2\pi f t \rangle = 0$

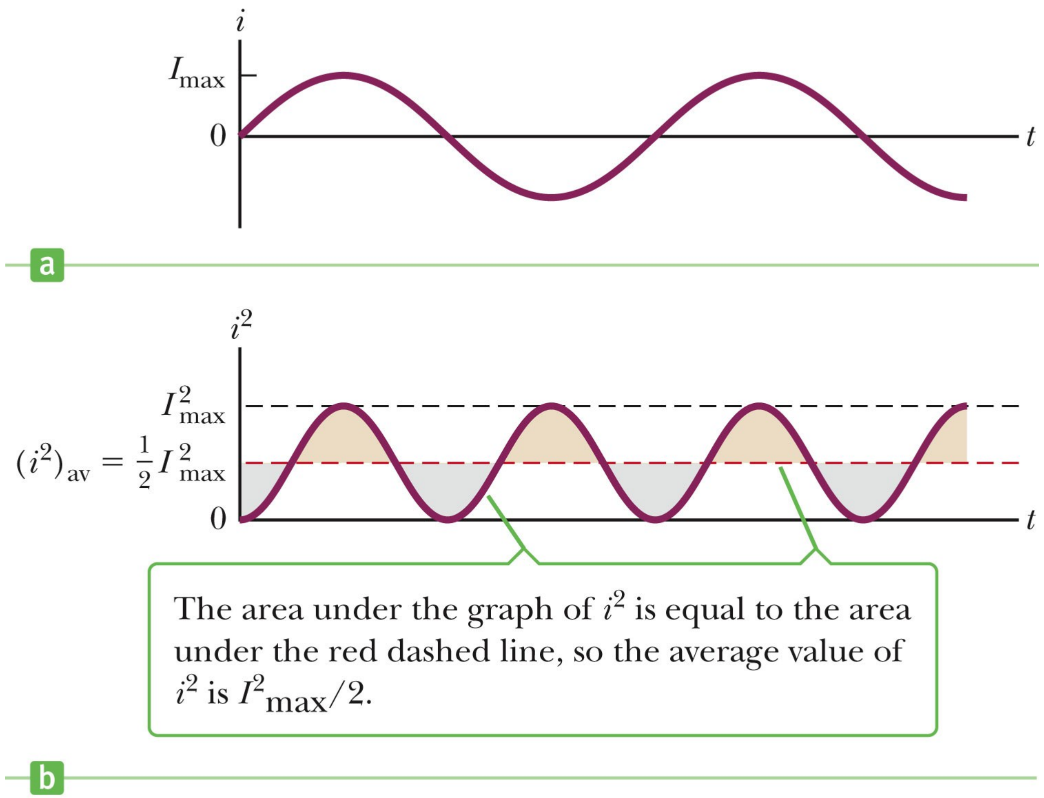
Average $\langle i^2 \rangle = \langle I_{max}^2 \sin^2 2\pi f t \rangle$

$$= I_{max}^2 \cdot \frac{1}{2} = \frac{I_{max}^2}{2}$$

$\therefore$ $I_{rms} = \sqrt{\frac{I_{max}^2}{2}} = \frac{I_{max}}{\sqrt{2}}$.

Similarly $\Delta V_{rms} = \frac{\Delta V_{max}}{\sqrt{2}}$

rms Graph



- The average value of i^2 is ½ I^2_{max}

Power Revisited

- The average power dissipated in resistor in an AC circuit carrying a current I is
  - $P_{av} = I^2_{max} R$

Notation Note

Table 21.1 Notation Used in This Chapter

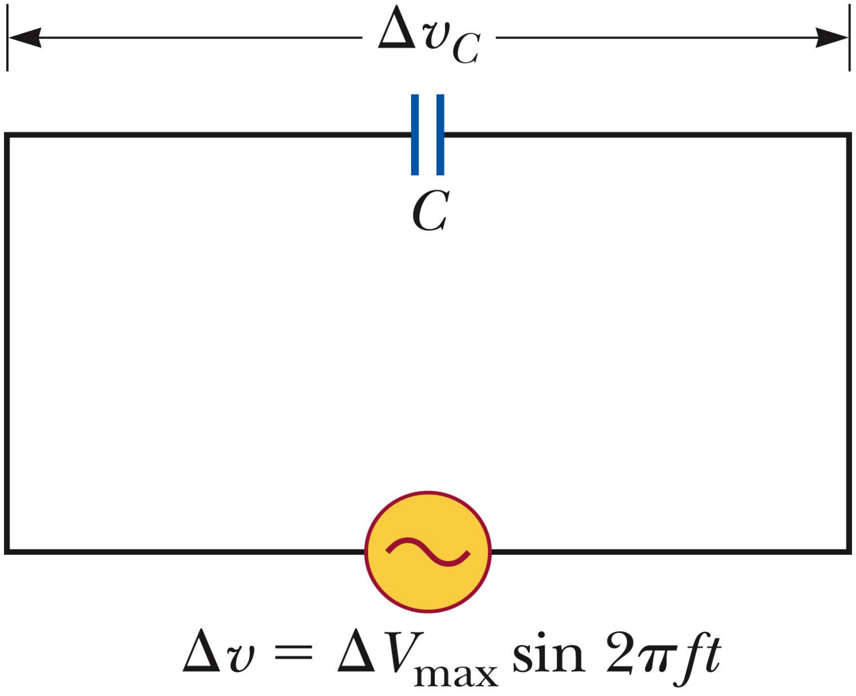
	Voltage	Current
Instantaneous value	Δv	i
Maximum value	ΔV_{max}	I_{max}
rms value	ΔV_{rms}	I_{rms}

Ohm's Law in an AC Circuit

- rms values will be used when discussing AC currents and voltages.
  - AC ammeters and voltmeters are designed to read rms values.
  - Many of the equations will be in the same form as in DC circuits.
- Ohm's Law for a resistor, R, in an AC circuit
  - $\Delta V_{R,rms} = I_{rms} R$
- Also applies to the maximum values of v and i

Capacitors in an AC Circuit

- Consider a circuit consisting of an AC source and a capacitor.
-

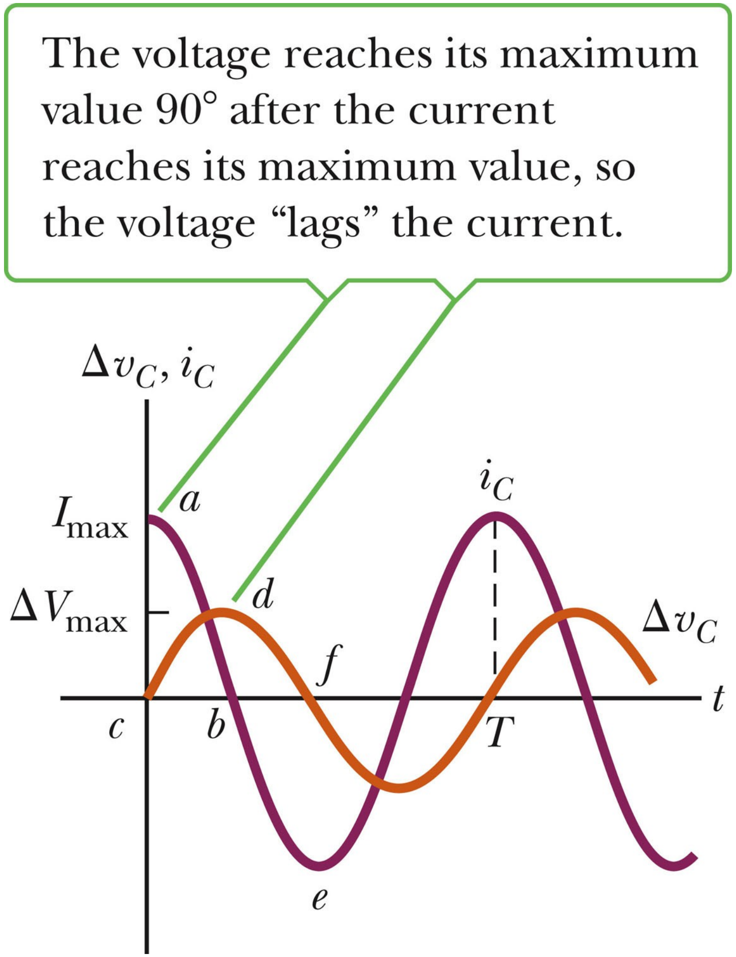


Capacitors, Cont.

- The current starts out at a large value and charges the plates of the capacitor.
  - There is initially no resistance to hinder the flow of the current while the plates are not charged.
- As the charge on the plates increases, the voltage across the plates increases and the current flowing in the circuit decreases.

More About Capacitors in an AC Circuit

- The current reverses direction.
- The voltage across the plates decreases as the plates lose the charge they had accumulated.
- The voltage across the capacitor lags behind the current by 90°



Capacitive Reactance and Ohm's Law

- The impeding effect of a capacitor on the current in an AC circuit is called the *capacitive reactance* and is given by

$$X_C = \frac{1}{2\pi f C}$$

  - When f is in Hz and C is in F, X_C will be in ohms
- Ohm's Law for a capacitor in an AC circuit
  - $\Delta V_{C,rms} = I_{rms} X_C$

Capacitive Reactance and Ohm's Law

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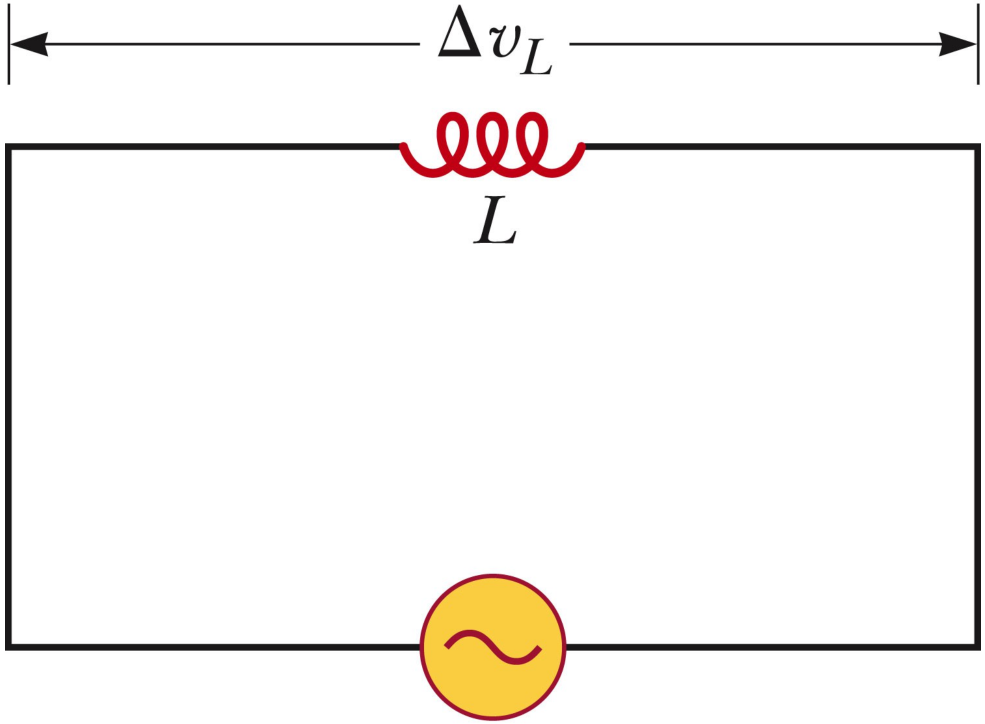
$$F = C/V \qquad X_c = \frac{1}{\left(\frac{C}{V}\right)s^{-1}} = \frac{V}{Cs^{-1}}$$

$$= \frac{V}{I} = \Omega$$

Inductors in an AC Circuit

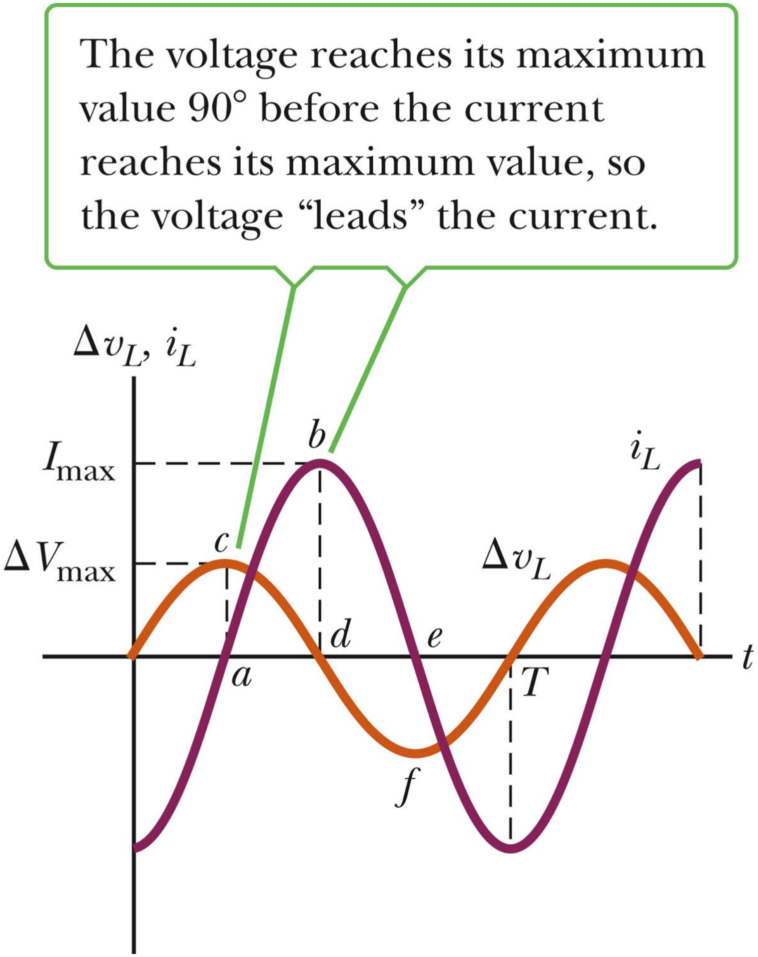
- Consider a circuit consisting of an AC source and an inductor.
-



$$\Delta v = \Delta V_{\max} \sin 2\pi f t$$

Inductors in an AC Circuit

- The current in the circuit is impeded by the back emf of the inductor.
- The voltage across the inductor always leads the current by 90°



Inductive Reactance and Ohm's Law

- The effective resistance of a coil in an AC circuit is called its *inductive reactance* and is given by
  - $X_L = 2≥ \ fL$
- When f is in Hz and L is in H, X_L will be in ohms
- Ohm's Law for the inductor
  - $\Delta V_{L,rms} = I_{rms} X_L$
  -

Inductive Reactance and Ohm's Law

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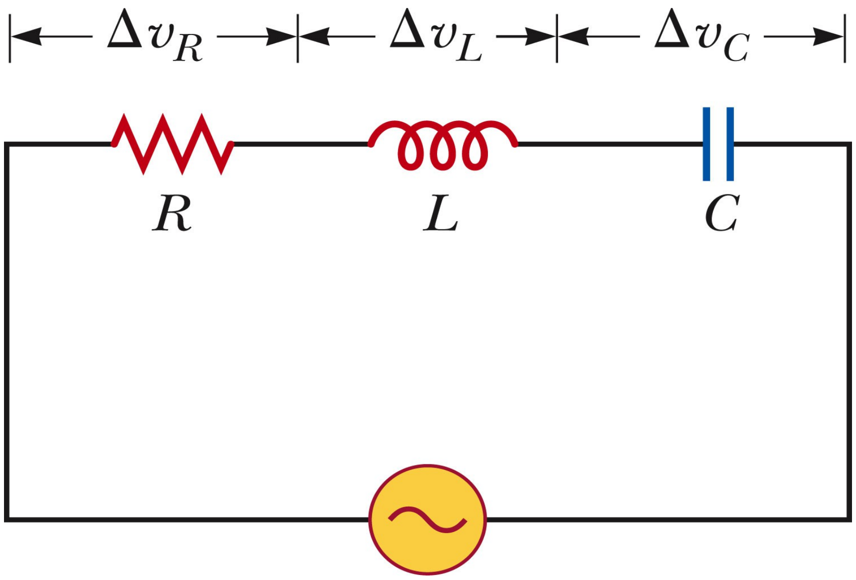
- Ohm's Law for the inductor
  - $\Delta V_{L,rms} = I_{rms} X_L$

$L \, di/dt = V$

$X_L \rightarrow s^{-1} H \rightarrow s^{-1} \, V / i s^{-1} = \frac{v}{i} = \Omega$

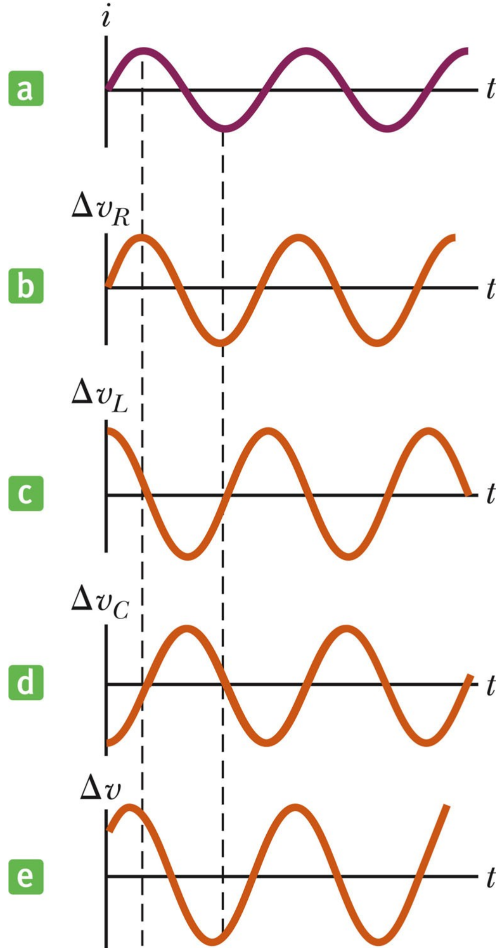
The RLC Series Circuit

- The resistor, inductor, and capacitor can be combined in a circuit.
- The current in the circuit is the same at any time and varies sinusoidally with time.



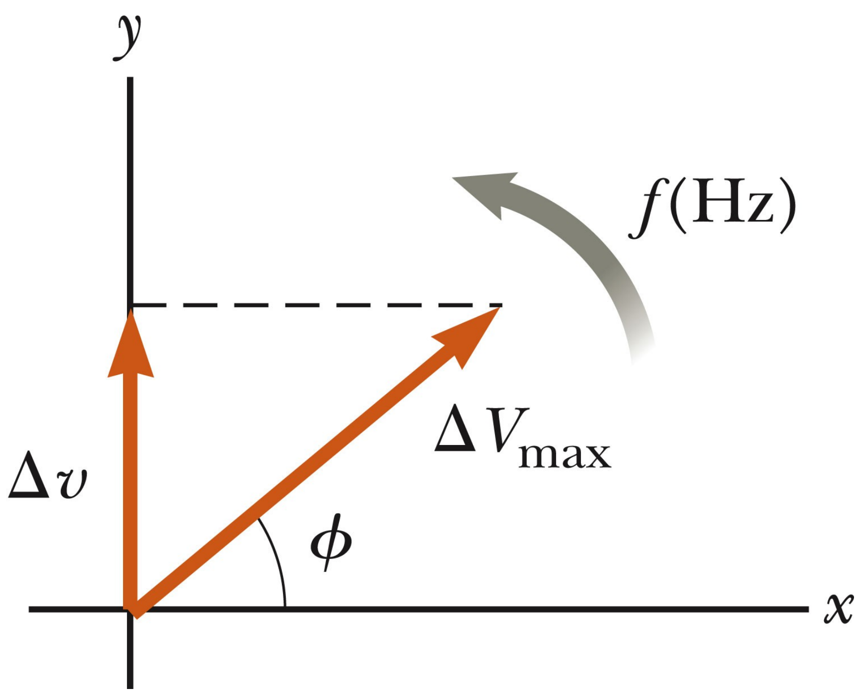
Current and Voltage Relationships in an RLC Circuit, Graphical Summary

- The instantaneous voltage across the resistor is in phase with the current.
- The instantaneous voltage across the inductor leads the current by 90°
- The instantaneous voltage across the capacitor lags the current by 90°



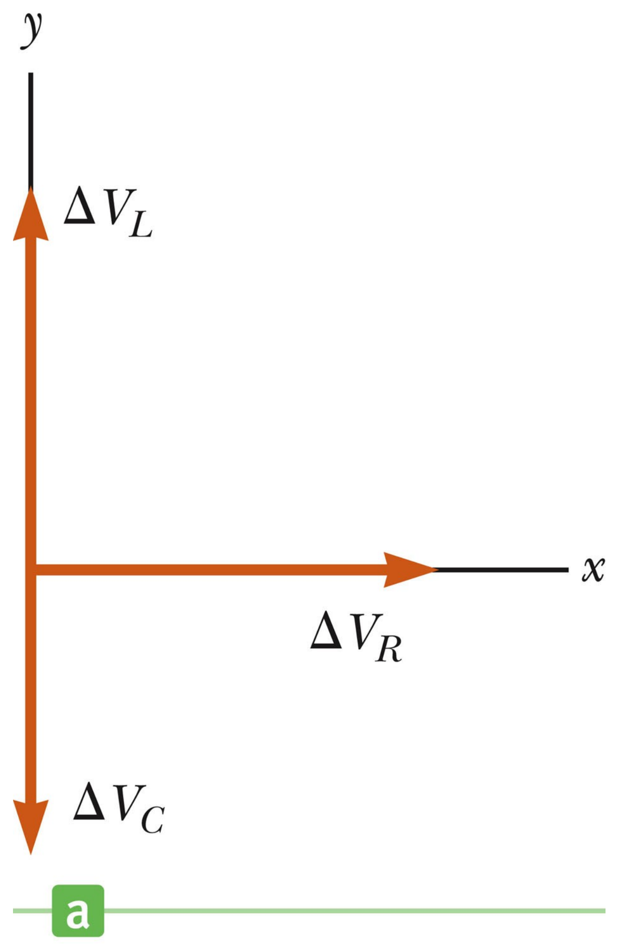
Phasor Diagrams

- To account for the different phases of the voltage drops, vector techniques are used.
- Represent the voltage across each element as a rotating vector, called a *phasor.*
- The diagram is called a *phasor diagram.*



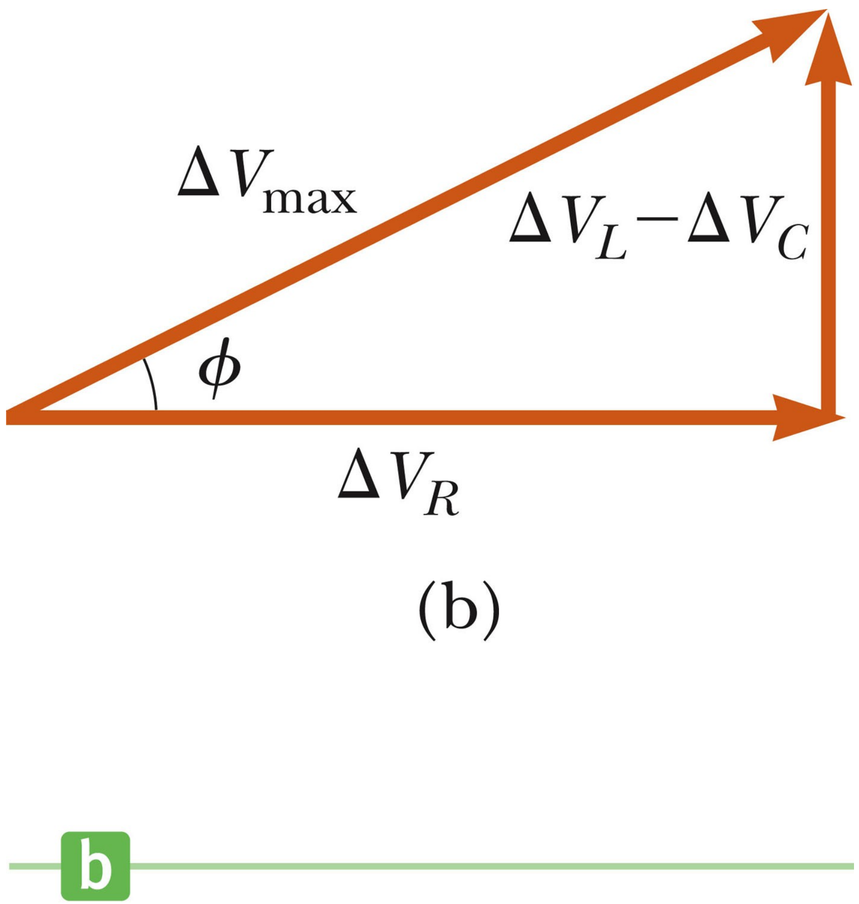
Phasor Diagram for RLC Series Circuit

- The voltage across the resistor is on the +x axis since it is in phase with the current.
- The voltage across the inductor is on the +y since it leads the current by 90°
- The voltage across the capacitor is on the –y axis since it lags behind the current by 90°



Phasor Diagram, Cont.

- The phasors are added as vectors to account for the phase differences in the voltages.
- ΔV_L and ΔV_C are on the same line and so the net y component is $\Delta V_L - \Delta V_C$

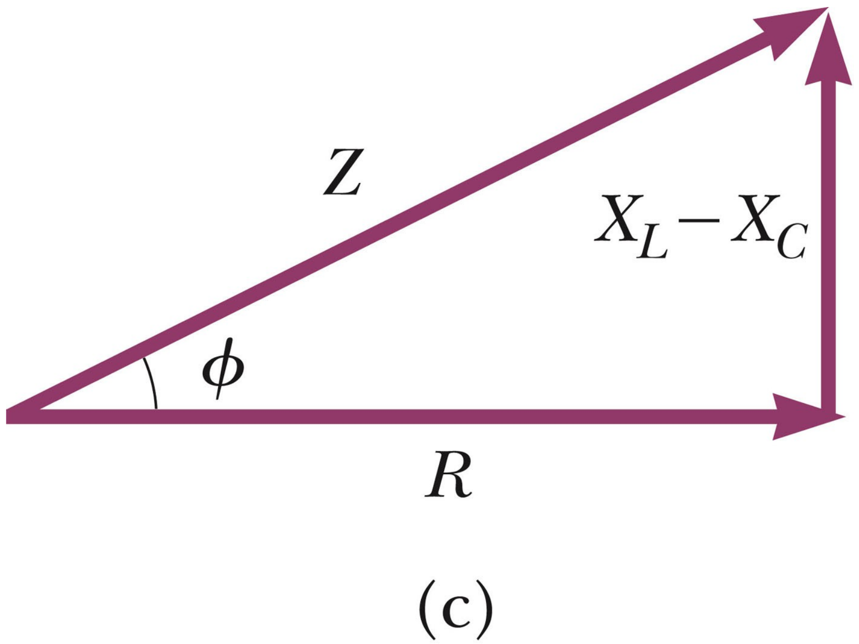


ΔV_{max} From the Phasor Diagram

- The voltages are not in phase, so they cannot simply be added to get the voltage across the combination of the elements or the voltage source.
-
- $$\Delta V_{max} = \sqrt{\Delta V_R^2 + (\Delta V_L - \Delta V_C)^2}$$
- $$\tan\phi = \frac{\Delta V_L - \Delta V_C}{\Delta V_R}$$
-
- ≥ is the *phase angle* between the current and the maximum voltage.
- The equations also apply to rms values.
-

Impedance of a Circuit

- The impedance, Z, can also be represented in a phasor diagram.
- $$Z = \sqrt{R^2 + (X_L - X_C)^2}$$
- $$\tan\phi = \frac{X_L - X_C}{R}$$

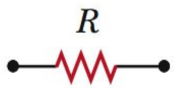
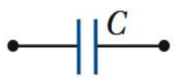
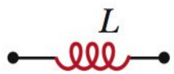
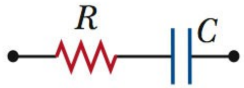
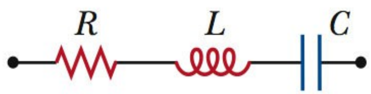


Impedance and Ohm's Law

- Ohm's Law can be applied to the impedance.
  - $\Delta V_{max} = I_{max} Z$
  - This can be regarded as a generalized form of Ohm's Law applied to a series AC circuit.
  -

Summary of Circuit Elements, Impedance and Phase Angles

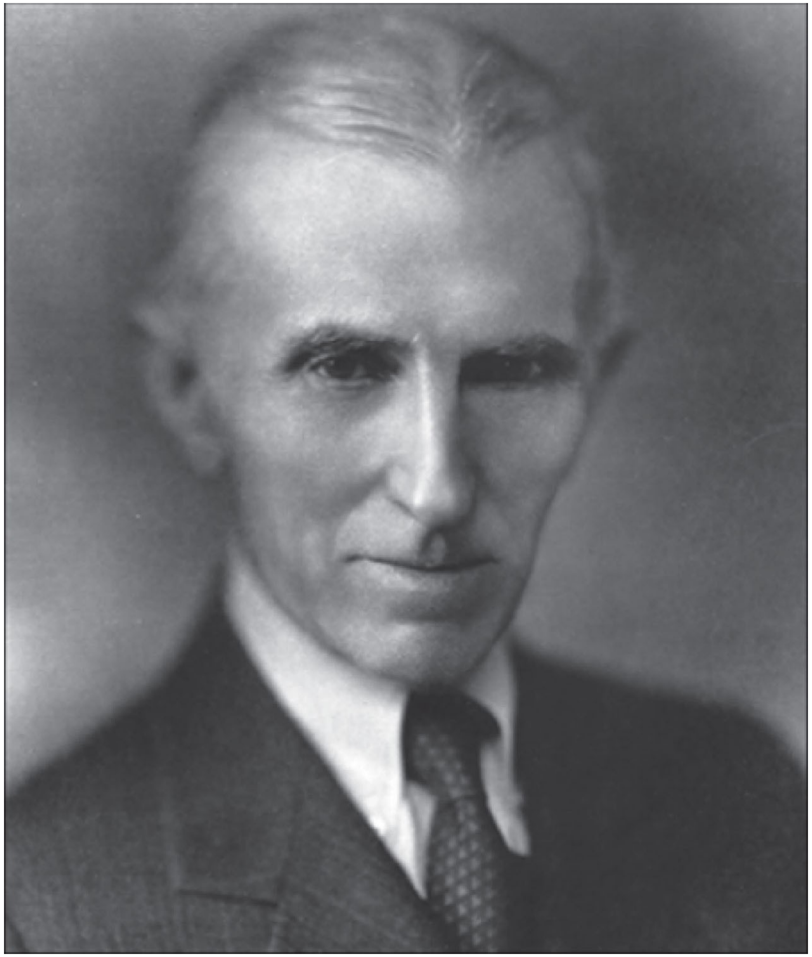
Table 21.2 Impedance Values and Phase Angles for Various Combinations of Circuit Elements

Circuit Elements	Impedance Z	Phase Angle ϕ
	R	$0°$
	X_C	$-90°$
	X_L	$+90°$
	$\sqrt{R^2 + X_C^2}$	Negative, between $-90°$ and $0°$
	$\sqrt{R^2 + X_L^2}$	Positive, between $0°$ and $90°$
	$\sqrt{R^2 + (X_L - X_C)^2}$	Negative if $X_C > X_L$ Positive if $X_C < X_L$

Note: In each case an AC voltage (not shown) is applied across the combination of elements (that is, across the dots).

Nikola Tesla

- 1865 – 1943
- Inventor
- Key figure in development of
  - AC electricity
  - High-voltage transformers
  - Transport of electrical power via AC transmission lines
- Beat Edison's idea of DC transmission lines



Problem Solving for RLC Circuits

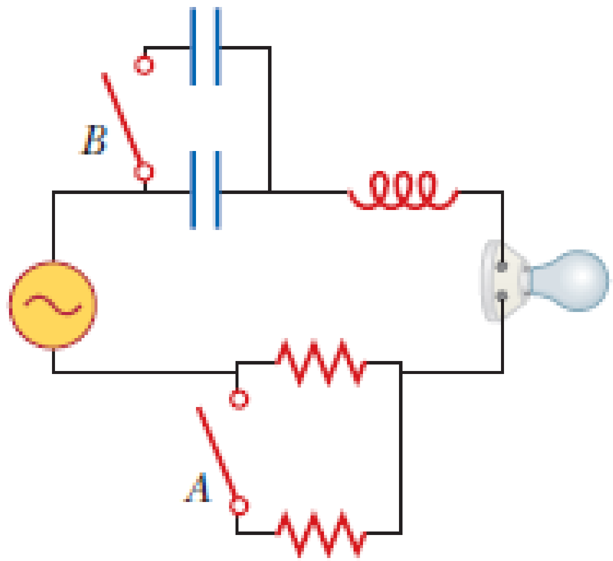
- Calculate the inductive and capacitive reactances, X_L and X_C
  - Be careful of units – use F, H, Ω
- Use X_L and X_C with R to find Z
- Find the maximum current or maximum voltage drop using Ohm's Law, ≥ $V_{max} = I_{max} Z$

Problem Solving, Cont.

- Calculate the voltage drops across the individual elements using the appropriate form of Ohm's Law.
- Obtain the phase angle.

Power in an AC Circuit

- No power losses are associated with pure capacitors and pure inductors in an AC circuit.
  - In a pure capacitor, during one-half of a cycle energy is stored and during the other half the energy is returned to the circuit.
  - In a pure inductor, the source does work against the back emf of the inductor and energy is stored in the inductor, but when the current begins to decrease in the circuit, the energy is returned to the circuit.



$$X_C \equiv \frac{1}{2\pi f C}$$

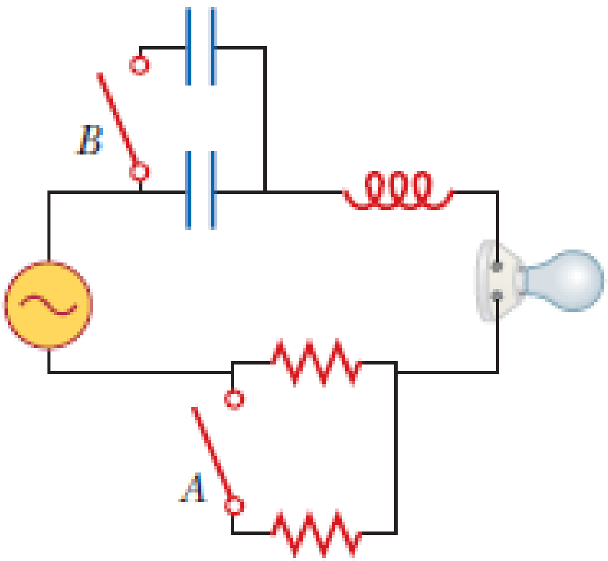
$$X_L \equiv 2\pi f L$$

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$\tan\phi = \frac{X_L - X_C}{R}$$

1. If switch A is closed in Fig, what happens to the impedance of the circuit? (a) It increases. (b) It decreases. (c) It doesn't change

2. Suppose $XL > XC$ in Fig. If switch A is closed, what happens to the phase angle? (a) It increases. (b) It decreases. (c) It doesn't change.2.



$$X_C \equiv \frac{1}{2\pi f C}$$

$$X_L \equiv 2\pi f L$$

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$\tan\phi = \frac{X_L - X_C}{R}$$

3. Suppose $XL > XC$ in Fig. If switch A is left open and switch B is closed, what happens to the phase angle? (a) It increases. (b) It decreases. (c) It doesn’t change.

4. Suppose $XL > XC$ in Fig with both switches open, a piece of iron is slipped into the inductor. During this process, what happens to the brightness of the bulb? (a) It increases. (b) It decreases. (c) It doesn’t change.

Choice (b). Closing switch A replaces a single resistor with a parallel combination of two resistors. Since the equivalent resistance of a parallel combination is always less than the lowes resistance in the combination, the total resistance of the circuit decreases, which causes the impedance $Z = \sqrt{R_{total}^2 + (X_L - X_C)^2}$ to decrease.

Choice (a). Closing switch A replaces a single resistor with a parallel combination of two resistors. Since the equivalent resistance of a parallel combination is always less than the lowest resistance in the combination, the total resistance of the circuit decreases, which causes the phase angle, $\phi = \tan^{-1}\left[(X_L - X_C)/R\right]$, to increase.

Choice (a). Closing switch B replaces a single capacitor with a parallel combination of two capacitors. Since the equivalent capacitance of a parallel combination is greater than that of either of the individual capacitors, the total capacitance increases, which causes the capacitive reactance $X_C = 1/2\pi fC$ to decrease. Thus, the net reactance, $X_L - X_C$, increases causing the phase angle, $\phi = \tan^{-1}\left[(X_L - X_C)/R\right]$, to increase.

Choice (b). Inserting an iron core in the inductor increases both the self-inductance and the inductive reactance, $X_L = 2\pi fL$. This means the net reactance, $X_L - X_C$, and hence the impedance, $Z = \sqrt{R_{total}^2 + (X_L - X_C)^2}$, increases, causing the current (and therefore, the bulb's brightness) to decrease.

Power in an AC Circuit, Cont.

- The average power delivered by the generator is converted to internal energy in the resistor.
  - $P_{av} = I_{rms}\Delta V_R = I_{rms}\Delta V_{rms} \cos \geq$
  - $\cos \geq$ is called the *power factor* of the circuit
- Phase shifts can be used to maximize power outputs.

A series RLC AC circuit has resistance R = 2.50 x 10^2 V, inductance L = 0.600 H, capacitance C = 3.50 mF, frequency f = 60.0 Hz, and maximum voltage ≥ Vmax = 1.50 x 10^2 V. Find **(a)** the impedance of the circuit, **(b)** the maximum current in the circuit, **(c)** the phase angle, and **(d)** the maximum voltages across the elements

$$X_L = 2\pi f L = 226\ \Omega \qquad X_C = 1/2\pi f C = 758\ \Omega$$

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$= \sqrt{(2.50 \times 10^2\ \Omega)^2 + (226\ \Omega - 758\ \Omega)^2} = \boxed{588\ \Omega}$$

$$I_{\max} = \frac{\Delta V_{\max}}{Z} = \frac{1.50 \times 10^2\ \text{V}}{588\ \Omega} = \boxed{0.255\ \text{A}}$$

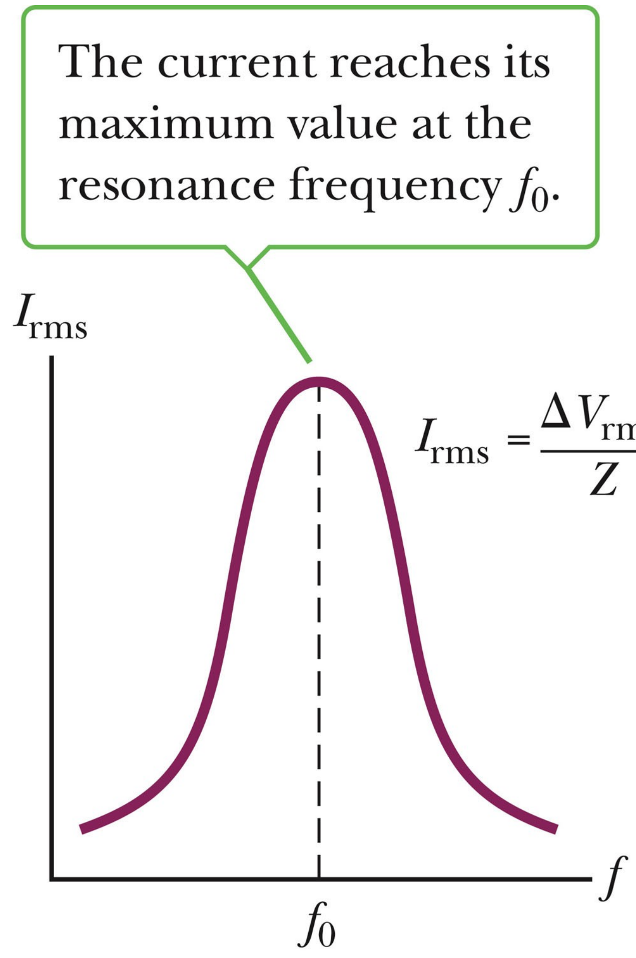
$$\phi = \tan^{-1}\frac{X_L - X_C}{R} = \tan^{-1}\left(\frac{226\ \Omega - 758\ \Omega}{2.50 \times 10^2\ \Omega}\right) = \boxed{-64.8^\circ}$$

$$\Delta V_{R,\max} = I_{\max} R = (0.255\ \text{A})(2.50 \times 10^2\ \Omega) = \boxed{63.8\ \text{V}}$$
$$\Delta V_{L,\max} = I_{\max} X_L = (0.255\ \text{A})(2.26 \times 10^2\ \Omega) = \boxed{57.6\ \text{V}}$$
$$\Delta V_{C,\max} = I_{\max} X_C = (0.255\ \text{A})(7.58 \times 10^2\ \Omega) = \boxed{193\ \text{V}}$$

Resonance in an AC Circuit

- *Resonance* occurs at the frequency, f_o, where the current has its maximum value.
  - To achieve maximum current, the impedance must have a minimum value.
  - This occurs when $X_L = X_C$
  - Then,

$$f_o = \frac{1}{2\pi\sqrt{LC}}$$



Resonance, Cont.

- Theoretically, if R = 0 the current would be infinite at resonance.
  - Real circuits always have some resistance.
- Tuning a radio
  - A varying capacitor changes the resonance frequency of the tuning circuit in your radio to match the station to be received.
- Metal Detector
  - The portal is an inductor, and the frequency is set to a condition with no metal present.
  - When metal is present, it changes the effective inductance, which changes the current.
  - The change in current is detected and an alarm sounds.

PROBLEM Consider a series *RLC* circuit for which $R = 1.50 \times 10^2\ \Omega$, $L = 20.0$ mH, $\Delta V_{rms} = 20.0$ V, and $f = 796\ s^{-1}$. (a) Determine the value of the capacitance for which the rms current is a maximum. (b) Find the maximum rms current in the circuit.

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad \rightarrow \quad \sqrt{LC} = \frac{1}{2\pi f_0} \quad \rightarrow \quad LC = \frac{1}{4\pi^2 f_0^{\ 2}}$$

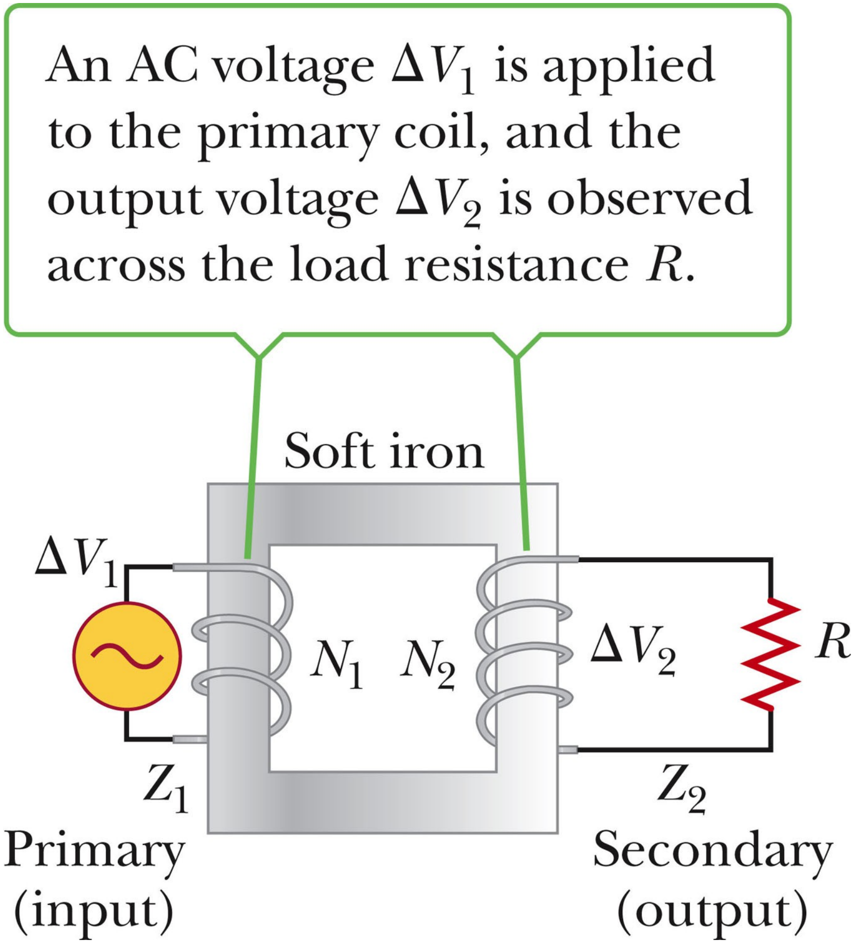
$$C = \frac{1}{4\pi^2 f_0^{\ 2} L}$$

$$C = \frac{1}{4\pi^2(796\ \text{Hz})^2(20.0 \times 10^{-3}\ \text{H})} = 2.00 \times 10^{-6}\ \text{F}$$

$$I_{rms} = \frac{\Delta V_{rms}}{Z} = \frac{20.0\ \text{V}}{1.50 \times 10^2\ \Omega} = 0.133\ \text{A}$$

Transformers

- An AC transformer consists of two coils of wire wound around a core of soft iron.
- The side connected to the input AC voltage source is called the *primary* and has N_1 turns.



Transformers, 2

- The other side, called the *secondary*, is connected to a resistor and has N_2 turns.
- The core is used to increase the magnetic flux and to provide a medium for the flux to pass from one coil to the other.
- The rate of change of the flux is the same for both coils.

Transformers, 3

- The voltages are related by

$$\Delta V_2 = \frac{N_2}{N_1} \Delta V_1$$

- When $N_2 > N_1$, the transformer is referred to as a *step up* transformer.
- When $N_2 < N_1$, the transformer is referred to as a *step down* transformer.

Transformer, Final

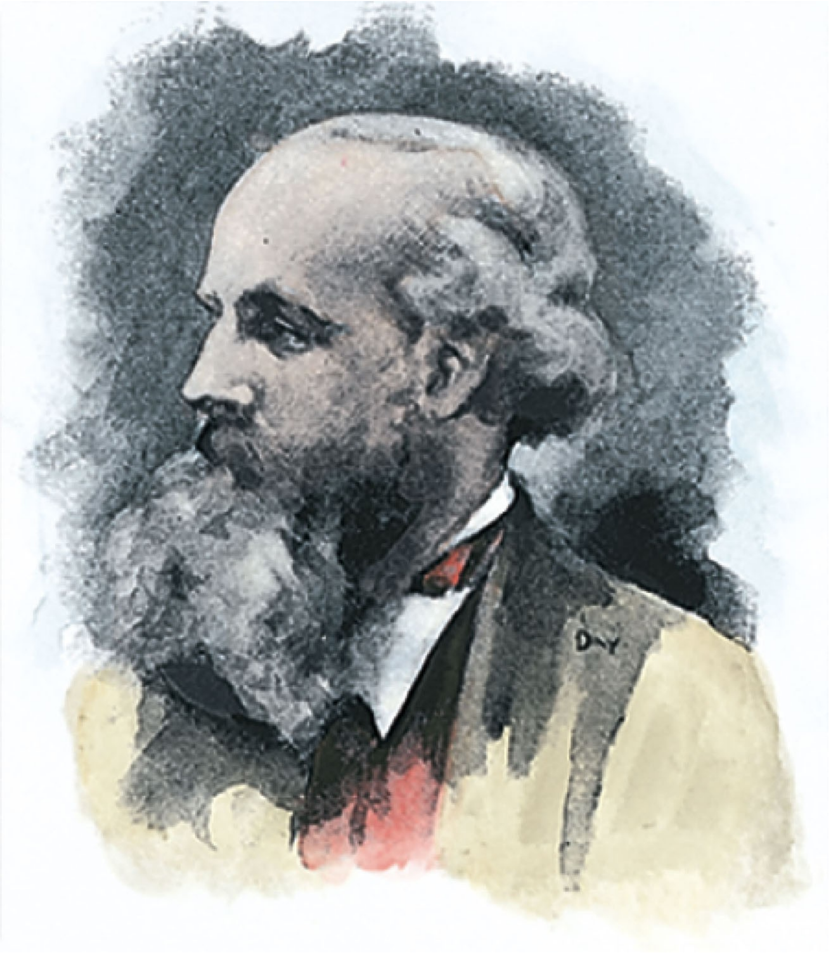
- The power input into the primary equals the power output at the secondary.
  - $I_1 \Delta V_1 = I_2 \Delta V_2$
- If the secondary voltage is higher, the secondary current must be lower.
- You don't get something for nothing.
  - This assumes an ideal transformer.
- In real transformers, power efficiencies typically range from 90% to 99%.

Electrical Power Transmission

- When transmitting electric power over long distances, it is most economical to use high voltage and low current. (conservation of energy V1I1 = V2I2)
  - Minimizes I^2R power losses
- In practice, voltage is stepped up to about 230 000 V at the generating station and stepped down to   20 000 V at the distribution station and finally to 120 V at the customer's utility pole.

James Clerk Maxwell

- 1831 – 1879
- Electricity and magnetism were originally thought to be unrelated.
- in 1865, James Clerk Maxwell provided a mathematical theory that showed a close relationship between all electric and magnetic phenomena.



More of Maxwell's Contributions

- Electromagnetic theory of light
- Kinetic theory of gases
- Nature of Saturn's rings
- Color vision
- Electromagnetic field interpretation
  - Led to Maxwell's Equations

Maxwell's Starting Points

- Electric field lines originate on positive charges and terminate on negative charges.
- Magnetic field lines always form closed loops – they do not begin or end anywhere.
- A varying magnetic field induces an emf and hence an electric field (Faraday's Law).
- Magnetic fields are generated by moving charges or currents (Ampère's Law).

Maxwell's Predictions

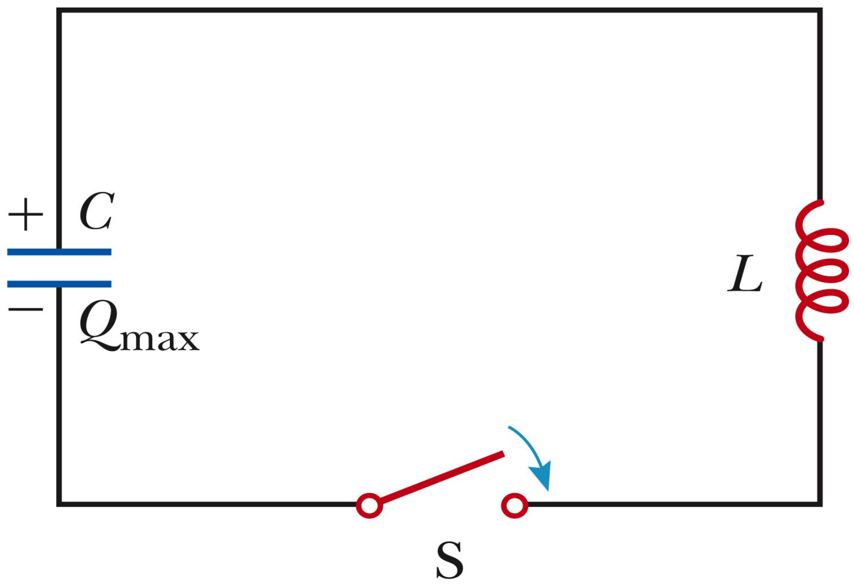
- Maxwell used these starting points and a corresponding mathematical framework to prove that *electric and magnetic fields play symmetric roles in nature.*
- He hypothesized that a changing electric field would produce a magnetic field.
- Maxwell calculated the speed of light to be 3×10^8 m/s.
- He concluded that visible light and all other electromagnetic waves consist of fluctuating electric and magnetic fields, with each varying field inducing the other.

Heinrich Rudolf Hertz

- 1857 – 1894
- First to generate and detect electromagnetic waves in a laboratory setting
- Showed radio waves could be reflected, refracted and diffracted
- The unit Hz is named for him.

Hertz's Basic LC Circuit

- When the switch is closed, oscillations occur in the current and in the charge on the capacitor.
- When the capacitor is fully charged, the total energy of the circuit is stored in the electric field of the capacitor.
  - At this time, the current is zero and no energy is stored in the inductor.

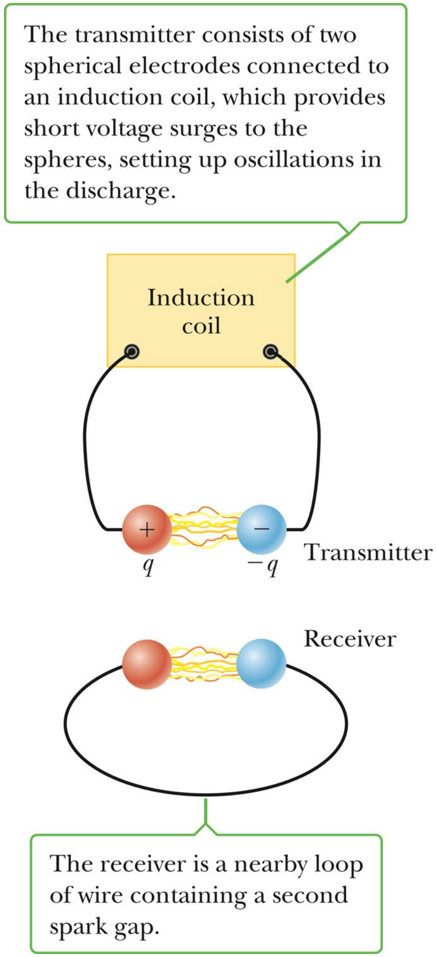


LC Circuit, Cont.

- As the capacitor discharges, the energy stored in the electric field decreases.
- At the same time, the current increases and the energy stored in the magnetic field increases.
- When the capacitor is fully discharged, there is no energy stored in its electric field.
  - The current is at a maximum and all the energy is stored in the magnetic field in the inductor.
- The process repeats in the opposite direction.
- There is a continuous transfer of energy between the inductor and the capacitor.

Hertz’s Experimental Apparatus

- An induction coil is connected to two large spheres forming a capacitor.
- Oscillations are initiated by short voltage pulses.
- The inductor and capacitor form the transmitter.



Hertz's Experiment

- Several meters away from the transmitter is the receiver.
  - This consisted of a single loop of wire connected to two spheres.
  - It had its own effect inductance, capacitance and natural frequency of oscillation.
- When the resonance frequencies of the transmitter and receiver matched, energy transfer occurred between them.

Hertz's Conclusions

- Hertz hypothesized the energy transfer was in the form of waves.
  - These are now known to be electromagnetic waves.
- Hertz confirmed Maxwell's theory by showing the waves existed and had all the properties of light waves.
  - They had different frequencies and wavelengths.

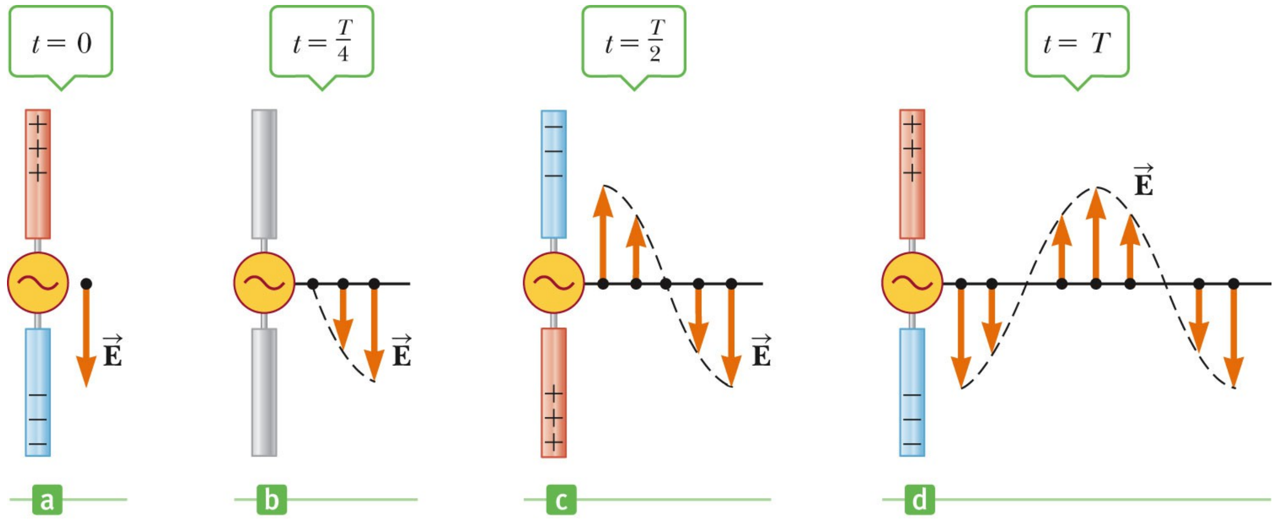
Hertz's Measurement of the Speed of the Waves

- Hertz measured the speed of the waves from the transmitter.
  - He used the waves to form an interference pattern and calculated the wavelength.
  - From $v = f \lambda$, v was found.
  - v was very close to 3×10^8 m/s, the known speed of light.
- This provided evidence in support of Maxwell's theory.

Electromagnetic Waves Produced by an Antenna

- When a charged particle undergoes an acceleration, it must radiate energy.
  - If currents in an ac circuit change rapidly, some energy is lost in the form of EM waves.
  - EM waves are radiated by any circuit carrying alternating current.
- An alternating voltage applied to the wires of an antenna forces the electric charges in the antenna to oscillate.

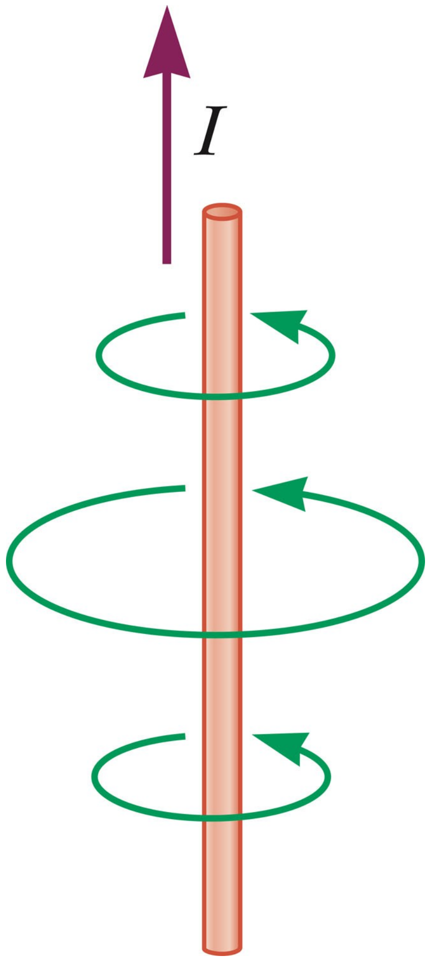
EM Waves by an Antenna, Cont.



- Two rods are connected to an ac source, charges oscillate between the rods (a).
- As oscillations continue, the rods become less charged, the field near the charges decreases and the field produced at t = 0 moves away from the rod (b).
- The charges and field reverse (c).
- The oscillations continue (d).

EM Waves by an Antenna, Final

- Because the oscillating charges in the rod produce a current, there is also a magnetic field generated.
- As the current changes, the magnetic field spreads out from the antenna.
- The magnetic field is perpendicular to the electric field.



Charges and Fields, Summary

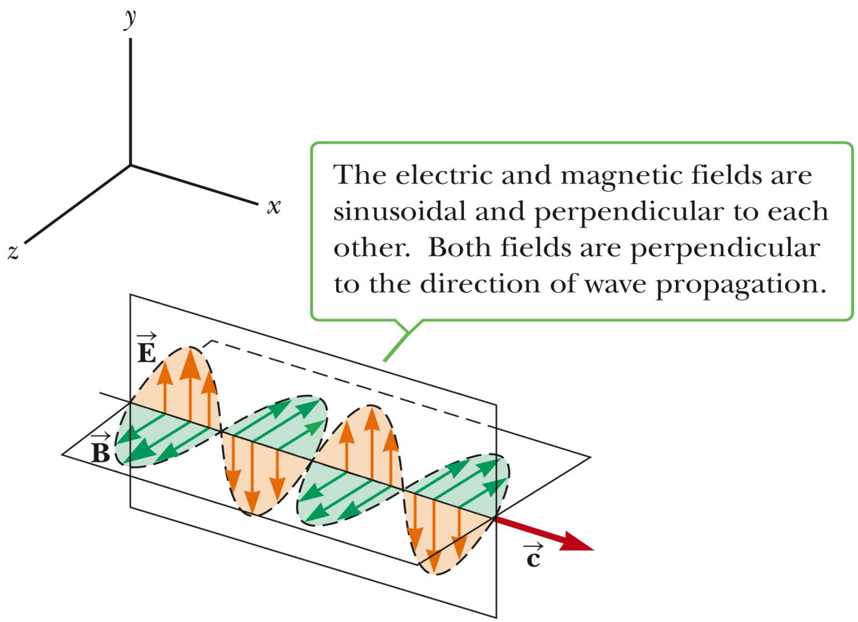
- Stationary charges produce only electric fields.
- Charges in uniform motion (constant velocity) produce electric and magnetic fields.
- Charges that are accelerated produce electric and magnetic fields and electromagnetic waves.
- An accelerating charge also radiates energy.

Electromagnetic Waves, Summary

- A changing magnetic field produces an electric field.
- A changing electric field produces a magnetic field.
- These fields are *in phase.*
  - At any point, both fields reach their maximum value at the same time.

Electromagnetic Waves are Transverse Waves

- The $\vec{E}$ and $\vec{B}$ fields are perpendicular to each other.
- Both fields are perpendicular to the direction of motion.
  - **Therefore, EM waves are transverse waves.**



Properties of EM Waves

- Electromagnetic waves are transverse waves.
- Electromagnetic waves travel at the speed of light.
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$$c = \frac{1}{\sqrt{\mu_o \varepsilon_o}}$$

– Because EM waves travel at a speed that is precisely the speed of light, *light is an electromagnetic wave.*

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Properties of EM Waves, 2

- The ratio of the electric field to the magnetic field is equal to the speed of light.

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

- Electromagnetic waves carry energy as they travel through space, and this energy can be transferred to objects placed in their path.

Properties of EM Waves, 3

- Energy carried by EM waves is shared equally by the electric and magnetic fields.

$$I = \frac{E_{max} B_{max}}{2\mu_o} = \frac{E^2_{max}}{2\mu_o c} = \frac{c}{2\mu_o} B^2_{max}$$

– Intensity (I) is average power per unit area.

Properties of EM Waves, Final

- Electromagnetic waves transport linear momentum as well as energy.
  - For complete absorption of energy U, $p=U/c$
  - For complete reflection of energy U, $p=(2U)/c$
- Radiation pressures can be determined experimentally.
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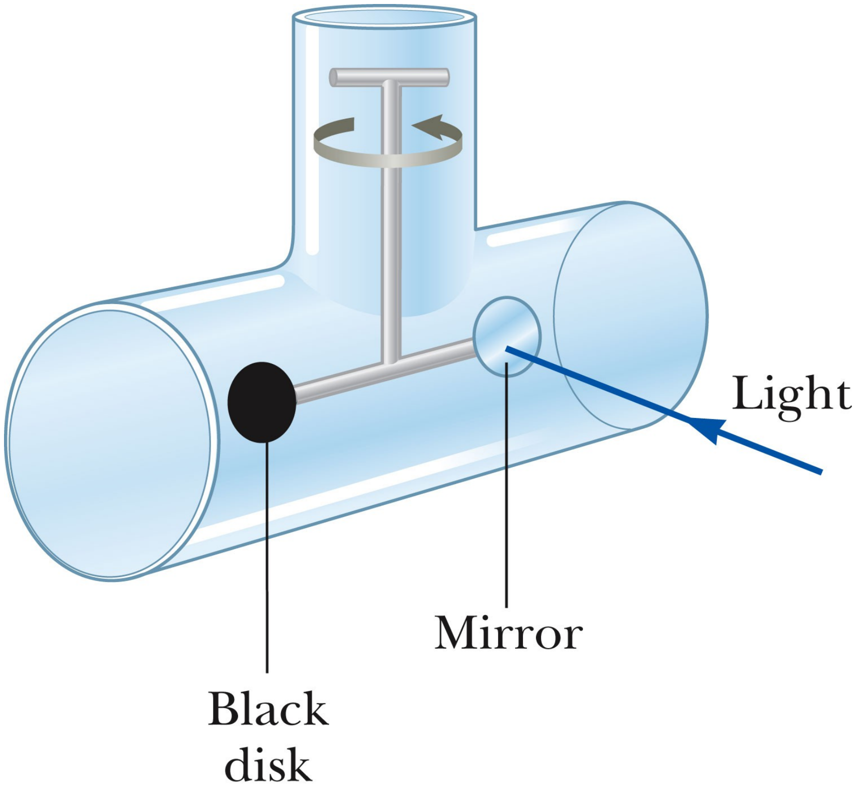
Determining Radiation Pressure

- This is an apparatus for measuring radiation pressure.
- In practice, the system is contained in a vacuum.
- The pressure is determined by the angle at which equilibrium occurs.



Properties of EM Waves, Summary

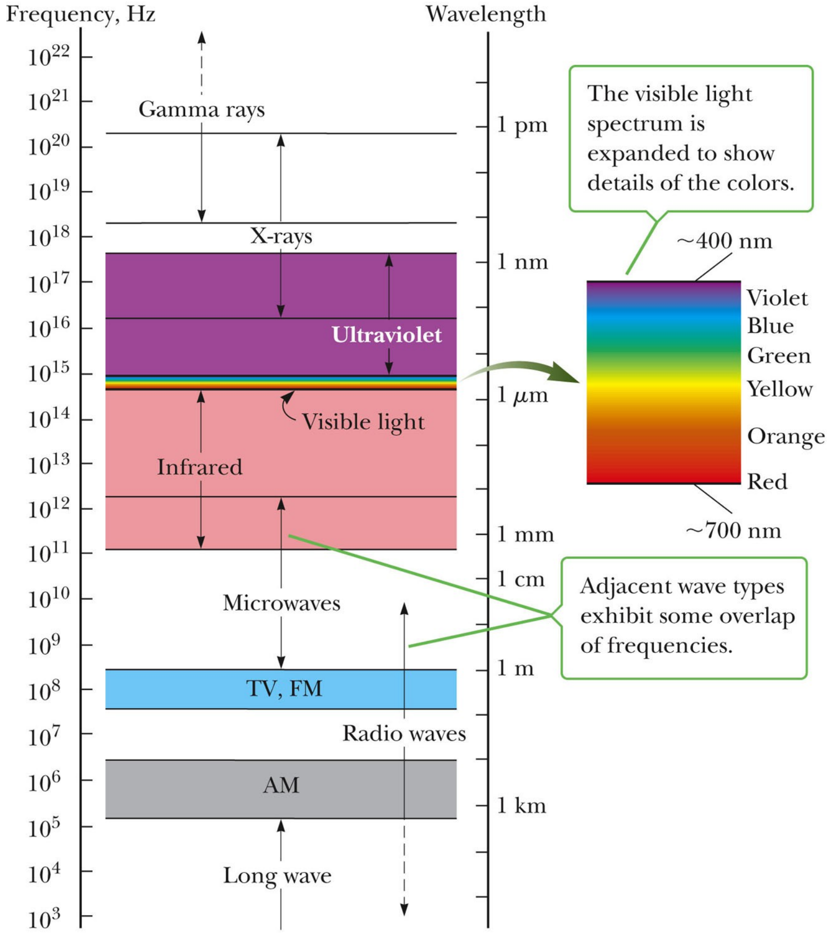
- EM waves travel at the speed of light.
- EM waves are transverse waves because the electric and magnetic fields are perpendicular to the direction of propagation of the wave and to each other.
- The ratio of the electric field to the magnetic field in an EM wave equals the speed of light.
- EM waves carry both energy and momentum, which can be delivered to a surface.

The Spectrum of EM Waves

- Forms of electromagnetic waves exist that are distinguished by their frequencies and wavelengths.
  - $c = f\lambda$
- Wavelengths for visible light range from 400 nm to 700 nm.
- There is no sharp division between one kind of EM wave and the next.

The EM Spectrum

- Note the overlap between types of waves.
- Visible light is a small portion of the spectrum.
- Types are distinguished by frequency or wavelength.



Notes on The EM Spectrum

- Radio Waves
  - Used in radio and television communication systems
- Microwaves
  - Wavelengths from about 1 mm to 30 cm
  - Well suited for radar systems
  - Microwave ovens are an application

Notes on the EM Spectrum, 2

- Infrared waves
  - Incorrectly called “heat waves”
  - Produced by hot objects and molecules
  - Wavelengths range from about 1 mm to 700 nm
  - Readily absorbed by most materials
- Visible light
  - Part of the spectrum detected by the human eye
  - Wavelengths range from 400 nm to 700 nm
  - Most sensitive at about 560 nm (yellow-green)

Notes on the EM Spectrum, 3

- Ultraviolet light
  - Covers about 400 nm to 0.6 nm
  - The Sun is an important source of uv light.
  - Most uv light from the sun is absorbed in the stratosphere by ozone.
- X-rays
  - Wavelengths range from about 10 nm to 10^{-4} nm
  - Most common source is acceleration of high-energy electrons striking a metal target
  - Used as a diagnostic tool in medicine

Notes on the EM Spectrum, Final

- Gamma rays
  - Wavelengths from about 10^{-10} m to 10^{-14} m
  - Emitted by radioactive nuclei
  - Highly penetrating and cause serious damage when absorbed by living tissue
- Looking at objects in different portions of the spectrum can produce different information.

Crab Nebula in Various Wavelengths

Doppler Effect and EM Waves

- A Doppler Effect occurs for EM waves, but differs from that of sound waves.
  - For sound waves, motion relative to a medium is most important.
    - For light waves, the medium plays no role since the light waves do not require a medium for propagation.
  - The speed of sound depends on its frame of reference.
    - The speed of EM waves is the same in all coordinate systems that are at rest or moving with a constant velocity with respect to each other.

Doppler Equation for EM Waves

- The Doppler effect for EM waves

$$f_o \approx f_s \left(1 \pm \frac{u}{c} \right)$$

- f_o is the observed frequency.
- f_s is the frequency emitted by the source.
- u is the *relative speed* of the source and the observer.
- The equation is valid only when u is much smaller than c.

Doppler Equation, Cont.

- The positive sign is used when the object and source are moving *toward* each other.
- The negative sign is used when the object and source are moving *away from* each other.
- Astronomers refer to a *red shift* when objects are moving away from the earth since the wavelengths are shifted toward the red end of the spectrum.
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