I have completed at least 50% of the reading and study-guide assignments associated with the lecture, as indicated on the course schedule.

A. True
B. False
C. But thanksgiving....

I am here today. Press A.
Summary: power has a phase angle; transformers

Physics 220 Fall 2013 Course Assignment Schedule

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Hint: This is a good time to look at the formula sheet and the CS. NEW concept: displacement current. New circuit element: none.

New terms. Displacement current.

I reopened warm-up exams for this exam thru Tuesday 11:00 pm.

I have key for exam 4.
If we deform surface $S_1$ (blue) into surface $S_2$ (orange), Ampere’s law for the magnetic circulation around loop $P$ appears to break down. Current flows through the blue surface of the loop but not the orange surface.
33-1. An air-filled circular parallel plate capacitor with radius \( a = 5.00 \text{ cm} \) and plate separation \( d = 2.00 \text{ mm} \), is driven by a 60 Hz alternating voltage with amplitude \( V = [01] \) _________ V. Naturally, the magnitude of the current is greatest at the instant when the voltage is zero. At such an instant, determine the magnitude of the (a) rate of change of electric flux in the capacitor, (b) displacement current in the capacitor, and (c) magnetic field near the edge of the capacitor. [(a) 100, 300 kV·m/s (b) 1.00, 3.00 \( \mu \text{A} \) (c) 5.00, 9.99 pT]}
33-2. Which of the following laws or principles are required to solve the problems described below. In each case, choose only one answer. If more than one response seems appropriate, choose the one most fundamental to the problem at hand. Possible responses are: (1) Gauss’s law of electrostatics, (2) Gauss’s law of magnetism, (3) Faraday’s law, (4) Ampere-Maxwell law, (5) Lorentz force law.

(a) Determine the magnetic field near a current carrying wire.
(b) Determine the trajectory of a proton in a uniform magnetic field.
(c) Determine the electric field inside a charged capacitor.
(d) Determine the magnetic field inside a charging capacitor.
(e) Determine the power delivered by a wind-turbine generator.
(f) Determine the electric field near the surface of a conductor.
(g) Determine the voltage difference between the ends of a metal bar moving in a magnetic field.
(h) Determine the total magnetic flux through a closed surface.
(i) Determine the voltage in the secondary winding of a transformer.
(j) The magnetic field produced by a moving charged particle.
33-3. Determine the validity of each of the following statements. Possible responses are (1) True or (2) False.

(a) Ampere’s law is physically equivalent to the Lorentz force law.
(b) Gauss’s law of electrostatics is physically equivalent to Gauss’s law of magnetism.
(c) Coulomb’s law is physically equivalent to Gauss’s law of electrostatics.
(d) The Biot-Savart law is physically equivalent to Faraday’s law.
(e) Lenz’s law is a corollary of Faraday’s law.
(f) Gauss’s law of electrostatics relates electric charge to electric flux.
(g) Gauss’s law of magnetism relates magnetic charge to magnetic flux.
(h) The Ampere-Maxwell law relates magnetic circulation to changing electric flux.
(i) The Ampere-Maxwell law relates magnetic circulation to electric current.
(j) Faraday’s law relates electric charge to changing magnetic flux.
33-4. Complete this problem on a separate sheet of paper and submit it with your CID# prominently displayed.

Name and state each of Maxwell’s equations and the Lorentz force law in plain English with no reference to symbols or acronyms.
Fundamental principles of E&M to date:

\[ \oint \mathbf{E} \cdot d\mathbf{A} = \frac{Q_E}{\varepsilon_0} \quad \oint \mathbf{E} \cdot d\mathbf{s} = -\frac{d\Phi_B}{dt} \]

\[ \oint \mathbf{B} \cdot d\mathbf{A} = 0 \quad \oint \mathbf{B} \cdot d\mathbf{s} = \mu_0 I_E \]
For clarity, temporarily invoke magnetic monopoles ($Q_B$) and magnetic monopole currents ($I_B$), and drop SI units.

**Gauss (E)**

\[ \oint E \cdot dA = Q_E \]

**Gauss (B)**

\[ \oint B \cdot dA = Q_B \]

**Faraday**

\[ \oint E \cdot ds = -I_B - \frac{d\Phi_B}{dt} \]

**Ampere-Maxwell**

\[ \oint B \cdot ds = I_E + \frac{d\Phi_E}{dt} \]

Are the equations symmetric?

Maxwell (1861) added a new term:
Maxwell’s Equations
(back to SI units and no magnetic monopoles)

Gauss (E)
\[ \oint E \cdot dA = \frac{Q_E}{\varepsilon_0} \]

Gauss (B)
\[ \oint B \cdot dA = 0 \]

Faraday
\[ \oint E \cdot ds = -\frac{d\Phi_B}{dt} \]

Ampere-Maxwell
\[ \oint B \cdot ds = \mu_0 \left( I_E + \varepsilon_0 \frac{d\Phi_E}{dt} \right) = \mu_0 (I_E + I_D) \]
There is a quantity analogous to electric current that flows across the gap between the plates of the capacitor, restoring the continuity of the circuit. This quantity is the time derivative of the electric flux and is called *displacement current*. 
33-1. An air-filled circular parallel plate capacitor with radius \( a = 5.00 \) cm and plate separation \( d = 2.00 \) mm, is driven by a 60 Hz alternating voltage with amplitude \( V = [01] \) ________ V. Naturally, the magnitude of the current is greatest at the instant when the voltage is zero. At such an instant, determine the magnitude of the (a) rate of change of electric flux in the capacitor, (b) displacement current in the capacitor, and (c) magnetic field near the edge of the capacitor. [(a) 100, 300 kV·m/s (b) 1.00, 3.00 \( \mu \)A (c) 5.00, 9.99 pT]
Comparison of Faraday’s and Maxwell’s terms
$I_D$ vs. $I_{\text{ext}}$ for a capacitor

$$I_D = \varepsilon_0 \frac{d\Phi_E}{dt} = \varepsilon_0 \frac{d(EA)}{dt} = \varepsilon_0 \frac{d(VA/d)}{dt} = \frac{\varepsilon_0 A}{d} \frac{dV}{dt} = C \frac{dV}{dt} = \frac{dQ}{dt} = I_{\text{ext}}$$
\[ \int \mathbf{B}_{\text{inside}} \cdot ds = 2\pi r B(r) = \mu_0 I_{D(\text{enclosed})} \]

\[ = \mu_0 \left( I_{D(\text{total})} \frac{r^2}{R^2} \right) = \mu_0 I_{\text{ext}} \frac{r^2}{R^2} \]

\[ \Rightarrow B(r) = \frac{\mu_0 I_{\text{ext}}}{2\pi R} \left( \frac{r}{R} \right) \]

\[ \int \mathbf{B}_{\text{outside}} \cdot ds = 2\pi r B(r) = \mu_0 I_{D(\text{enclosed})} \]

\[ = \mu_0 I_{D(\text{total})} = \mu_0 I_{\text{ext}} \]

\[ \Rightarrow B(r) = \frac{\mu_0 I_{\text{ext}}}{2\pi r} \]
33-2. Which of the following laws or principles are required to solve the problems described below. In each case, choose only one answer. If more than one response seems appropriate, choose the one most fundamental to the problem at hand. Possible responses are: (1) Gauss’s law of electrostatics, (2) Gauss’s law of magnetism, (3) Faraday’s law, (4) Ampere-Maxwell law, (5) Lorentz force law.

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(i) The Ampere-Maxwell law relates magnetic circulation to electric current.
(j) Faraday’s law relates electric charge to changing magnetic flux.
33-4. Complete this problem on a separate sheet of paper and submit it with your CID# prominently displayed.

Name and state each of Maxwell’s equations and the Lorentz force law in plain English with no reference to symbols or acronyms.
**Gauss's law of electricity**
The net electric flux exiting a closed surface is proportional to the net electric charge enclosed by the surface.

**Gauss's law of magnetism**
The net magnetic flux exiting a closed surface is always zero.

**The Ampere-Maxwell law**
The magnetic circulation around a closed loop is proportional to the net electric current flowing through the loop, including the actual flow of electric charge as well as the displacement current, which is the time derivative of the electric flux. The positive directions of circulation, current and flux are related by the right-hand rule.

**Faraday’s law**
The electric circulation (or emf) around a closed loop is proportional to the negative time derivative of the magnetic flux through the loop, where the positive circulation and flux directions are related by the right-hand rule.

**The Lorentz force law**
An electric charge moving in the presence of electric and magnetic fields experiences a vector force per unit charge that is equal to the sum of the electric field and the cross product of the velocity with the magnetic field.
1D classical wave equation
\[
\frac{d^2 f}{dx^2} = \frac{1}{v^2} \frac{d^2 f}{dt^2}
\]

3D classical wave equation
\[
\nabla^2 f = \frac{1}{v^2} \frac{d^2 f}{dt^2}
\]

Laplacian: \[
\nabla^2 f \equiv \frac{d^2 f}{dx^2} + \frac{d^2 f}{dy^2} + \frac{d^2 f}{dz^2}
\]
Simplest solution: the plane wave
(complex exponential form)

\[ f(x, t) = e^{i\phi} = e^{i(kx - \omega t)}. \]

\[
\frac{df}{dx} = ike^{i(kx - \omega t)} \quad \frac{d^2 f}{dx^2} = -k^2 e^{i(kx - \omega t)}
\]

\[
\frac{df}{dt} = -i\omega e^{i(kx - \omega t)} \quad \frac{d^2 f}{dt^2} = -\omega^2 e^{i(kx - \omega t)}
\]

\[
\frac{d^2 f}{dx^2} = \frac{k^2}{\omega^2} \frac{d^2 f}{dt^2} = \frac{1}{\nu^2} \frac{d^2 f}{dt^2} \quad \text{where} \quad \nu = \frac{\omega}{k}
\]
Simplest solution: the plane wave
(trigonometric form)

\[ f(x, t) = A \sin(kx - \omega t) \]

\[ \frac{df}{dx} = Ak \cos(kx - \omega t) \]

\[ \frac{df}{dt} = -A \omega \cos(kx - \omega t) \]

\[ \frac{d^2 f}{dx^2} = -Ak^2 \sin(kx - \omega t) \]

\[ \frac{d^2 f}{dt^2} = -A \omega^2 \sin(kx - \omega t) \]

\[ \frac{d^2 f}{dx^2} = \frac{k^2}{\omega^2} \frac{d^2 f}{dt^2} = \frac{1}{v^2} \frac{d^2 f}{dt^2} \]

where \( v = \frac{\omega}{k} \)
General wave-equation solution

Let $f$ be written as $f(\phi)$ where $\phi = kx - \omega t$.

\[ \frac{d^2 f}{dx^2} = \frac{d^2 f}{d\phi^2} \left( \frac{d\phi}{dx} \right)^2 + \frac{df}{d\phi} \left( \frac{d^2 \phi}{dx^2} \right) = k^2 \frac{d^2 f}{d\phi^2} \]

\[ \frac{d^2 f}{dt^2} = \frac{d^2 f}{d\phi^2} \left( \frac{d\phi}{dt} \right)^2 + \frac{df}{d\phi} \left( \frac{d^2 \phi}{dt^2} \right) = \omega^2 \frac{d^2 f}{d\phi^2} \]

\[ \frac{d^2 f}{dx^2} = \frac{k^2}{\omega^2} \frac{d^2 f}{dt^2} = \frac{1}{v^2} \frac{d^2 f}{dt^2} \quad \text{where} \quad v = \frac{\omega}{k}. \]
Next time.
Plane wave parameters

\[ f(x, t) = A \sin(kx - \omega t) \rightarrow A \sin(k \cdot x - \omega t) \]

Amplitude \( A \) \hspace{1cm} \text{Phase} \ \phi = kx - \omega t \hspace{1cm} \text{Velocity} \ \nu = \frac{\omega}{k}

Wavelength \ \lambda \hspace{1cm} \text{Period} \ T

Angular wavevector \( k = \frac{2\pi}{\lambda} \) \hspace{1cm} \text{Angular frequency} \ \omega = \frac{2\pi}{T}

Cyclic wavevector \( \tilde{k} = \frac{1}{\lambda} \) \hspace{1cm} \text{Cyclic frequency} \ \nu = \frac{1}{T}

Think of wavevector (also called wave number) as a spatial rather than a temporal frequency (1/m units).
Spatial periodicity and frequency
Wave velocity

String: \[ v = \sqrt{\frac{\text{tension}}{\lambda_m}} \]

Sound: \[ v = \sqrt{\frac{\text{pressure}}{\rho_m}} \]

Collection of masses and springs: \[ v = \text{spacing} \cdot \sqrt{\frac{\text{stiffness}}{\text{mass}}} \]

Shallow water: \[ v = \sqrt{g \cdot \text{depth}} \]

Deep water: \[ v(k) = \sqrt{\frac{g}{k}} \]
Wave superposition

Wave Packets, Standing Waves, Beats

http://paws.kettering.edu/~drussell/Demos/superposition/superposition.html

Standing Waves and Phasors

http://resonanceswavesandfields.blogspot.com/2008/02/complex-phasor-representation-of.html
Maxwell’s Equations

Integral Form

\[ \oint E \cdot dA = \frac{Q}{\varepsilon_0} \quad \oint B \cdot dA = 0 \quad \oint E \cdot ds = -\frac{d}{dt} \oint B \cdot dA \quad \oint B \cdot ds = \mu_0 I + \mu_0 \varepsilon_0 \frac{d}{dt} \oint E \cdot dA \]

Differential Form (extra, not on test)

\[ \nabla \cdot E = \frac{\rho}{\varepsilon_0} \quad \nabla \cdot B = 0 \quad \nabla \times E = -\frac{dB}{dt} \quad \nabla \times B = \mu_0 J + \mu_0 \varepsilon_0 \frac{dE}{dt} \]

These two forms of the equations are shown to be equivalent via two important theorems from vector calculus.

Gauss divergence theorem: \[ \int_V (\nabla \cdot \mathbf{F})dV = \oint_A \mathbf{F} \cdot d\mathbf{A} \]

Stokes curl theorem: \[ \int_A (\nabla \times \mathbf{F}) \cdot d\mathbf{A} = \oint_s \mathbf{F} \cdot ds \]
Empty space: \( \rho = \mathbf{J} = 0 \)

Useful Identity: \( \nabla \times (\nabla \times \mathbf{F}) = \nabla (\nabla \cdot \mathbf{F}) - \nabla^2 \mathbf{F} \)

\( \begin{align*}
(1) \quad \nabla \cdot \mathbf{E} &= 0 \\
(2) \quad \nabla \cdot \mathbf{B} &= 0 \\
(3) \quad \nabla \times \mathbf{E} &= -\frac{d\mathbf{B}}{dt} \\
(4) \quad \nabla \times \mathbf{B} &= \mu_0 \varepsilon_0 \frac{d\mathbf{E}}{dt}
\end{align*} \)

\[
\frac{d^2 \mathbf{B}}{dt^2} = \frac{d}{dt} \left( \frac{d\mathbf{B}}{dt} \right) = \frac{d}{dt} \left( -\nabla \times \mathbf{E} \right) = -\nabla \times \frac{d\mathbf{E}}{dt} = -\nabla \times \left( \frac{\nabla \times \mathbf{B}}{\mu_0 \varepsilon_0} \right) = \frac{-1}{\mu_0 \varepsilon_0} \left( \nabla (\nabla \cdot \mathbf{B}) - \nabla^2 \mathbf{B} \right) = \frac{\nabla^2 \mathbf{B}}{\mu_0 \varepsilon_0}
\]

\[
\frac{d^2 \mathbf{E}}{dt^2} = \frac{d}{dt} \left( \frac{d\mathbf{E}}{dt} \right) = \frac{d}{dt} \left( \frac{\nabla \times \mathbf{B}}{\mu_0 \varepsilon_0} \right) = \frac{\nabla \times \left( -\nabla \times \mathbf{E} \right)}{\mu_0 \varepsilon_0} = \frac{-1}{\mu_0 \varepsilon_0} \left( \nabla (\nabla \cdot \mathbf{E}) - \nabla^2 \mathbf{E} \right) = \frac{\nabla^2 \mathbf{E}}{\mu_0 \varepsilon_0}
\]

\[\nabla^2 \mathbf{B} = \mu_0 \varepsilon_0 \frac{d^2 \mathbf{B}}{dt^2} = \frac{1}{v^2} \frac{d^2 \mathbf{B}}{dt^2}\]

\[\nabla^2 \mathbf{E} = \mu_0 \varepsilon_0 \frac{d^2 \mathbf{E}}{dt^2} = \frac{1}{v^2} \frac{d^2 \mathbf{E}}{dt^2}\]

\[v = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = \frac{1}{\sqrt{(4\pi \times 10^{-7} \text{Tm/A})(8.85 \times 10^{-12} \text{ F/m})}} = 3.00 \times 10^8 \text{ m/s} \quad \text{Speed of Light !!!}\]
And God said,

\[ \oint E \cdot dA = \frac{Q}{\varepsilon_0} \]

\[ \oint B \cdot dA = 0 \]

\[ \oint E \cdot ds = -\frac{d}{dt} \oint B \cdot dA \]

\[ \oint B \cdot ds = \mu_0 I + \mu_0 \varepsilon_0 \frac{d}{dt} \oint E \cdot dA \]

and there was light. (Genesis 1:3)
iClicker Quiz

I have completed at least 50% of the reading and study-guide assignments associated with the lecture, as indicated on the course schedule.

A. True
B. False

E and B field: What direction do they point? How to calculate one from the other.

Poynting Vector: directions and Calculation of intensity, Energy densities, average and peak-
Momentum & pressure
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**Summary:** Power has a phase angle; transformers

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**Hint:** This is a good time to look at the formula sheet and the CS. NEW concept: displacement current. New circuit element: none.

New terms. Displacement current.

I reopened warm-up exams for this exam thru Tuesday 11:00 pm.
Electromagnetic spectrum
Electromagnetic spectrum
(images of the Crab Nebula)

X-rays

Visible

Infrared

Radio
Electromagnetic wave polarization

\[ \mathbf{E} \times \mathbf{B} \approx c \]
The E&M Wave Dance
The electric field of a plane electromagnetic wave in free space is given by \( E = E_x = -7.2 \sin (z + 3 \times 10^8 t) \) V/m. The wave is travelling in the direction of 1? (1) \( \hat{i} \) (2) \( -\hat{i} \) (3) \( \hat{j} \) (4) \( -\hat{j} \) (5) \( \hat{k} \) (6) \(-\hat{k}\) and has a cyclic frequency of 2F hertz. The maximum value of the electric field of the wave will be 3F SI units and the maximum value of the magnetic field will be 4F SI units.

**Answer:**

The wave crest is a place of constant phase: \( z + 3 \times 10^8 t = \text{const} \Rightarrow z = \text{const} - 3 \times 10^8 t \), so the wave travels in the \(-\hat{k}\) direction.

Travelling wave form is \( \sin (kz - \omega t) \) so \( \nu = \frac{\omega}{2\pi} = 3 \times 10^8 \text{s}^{-1}/2\pi = 4.77 \times 10^7 \text{Hz} \).

Maximum \( E \) is just the amplitude: 7.2 V/m.

\( B = E/c = (7.2)/(3 \times 10^8) = 24 \text{ nT} \).
\[ \nabla \times \mathbf{E} = -\frac{d\mathbf{B}}{dt} \quad \Rightarrow \quad \frac{dE_x}{dz} = -\frac{dB_y}{dt} \]

Let \( E_x = E_0 e^{i(kz-\omega t)} \) and \( B_y = B_0 e^{i(kz-\omega t)} \).

\[ \Downarrow \]

\[ E_0 (ik) e^{i(kz-\omega t)} = -B_0 (-i\omega) e^{i(kz-\omega t)} \]

\[ \Downarrow \]

\[ \frac{E_0}{B_0} = \frac{\omega}{k} = c \]
Maxwell’s Ether

Figure 2  Maxwell’s vortex model of the magnetic field. The rotating vortices represent lines of magnetic force. They mesh with small particles that act like gear wheels. In free space the particles are restrained from moving, except for a small elastic reaction (the displacement current), but in a conducting wire they are free to move. Their motion constitutes an electric current, which in turn sets the vortices in rotation, creating the magnetic field around the wire. A and B represent current through a wire, and p and q represent an induced current in an adjacent wire. (Redrawn from The Scientific Papers of James Clerk Maxwell, Vol. I, fig. 2 after p. 488.)
The Michelson and Morley Experiment
(extra material, not on test)

\[ \Delta t = \frac{L}{c+v} + \frac{L}{c-v} = \frac{2L/c}{1 - \frac{v^2}{c^2}} \]

http://galileoandeinstein.physics.virginia.edu/more_stuff/flashlets/mmexpt6.htm
Phase vs. Group velocity
(extra material, not on test)

\[ f(\phi = kx - \omega t) \Rightarrow \frac{d^2 f}{dx^2} = \frac{1}{v_p^2} \frac{d^2 f}{dt^2} \quad \text{where} \quad v_p = \frac{\omega}{k} \]

\[ \omega \rightarrow \omega(k), \text{a phenomenon called dispersion} \Rightarrow v_g = \frac{d\omega}{dk} \]

To know the expression for velocity is to know the dispersion relation that relates the spatial and temporal frequencies.
Massive and massless dispersion relations
(extra material, not on test)

Quantum mechanics: $U = \hbar \omega$ and $p = \hbar k$

$$U = \frac{p^2}{2m} = \frac{\hbar^2 k^2}{2m} \quad \Rightarrow \quad \omega = \frac{U}{\hbar} = \frac{\hbar k^2}{2m}$$

Massive particles (e.g. electrons)

$$v_p = \frac{\omega}{k} = \frac{\hbar k}{2m} \quad v_g = \frac{d\omega}{dk} = \frac{\hbar k}{m}$$

Massless particles (e.g. photons)

$$U = pc = \hbar kc \quad \Rightarrow \quad \omega = \frac{U}{\hbar} = kc$$

$$v_p = v_g = \frac{\omega}{k} = \frac{d\omega}{dk} = c$$
**Summary:** power has a phase angle; transformers

**Physics 220 Fall 2013 Course Assignment Schedule**

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**Hint:** This is a good time to look at the formula sheet and the CS. **NEW concept:** displacement current. **New circuit element:** none.

**New terms. Displacement current.**

**I reopened warm-up exams for this exam thru Tuesday 11:00 pm.**

**Remember:** Exam #5 Runs thru Wed Dec. 4
Light Energy

Equal electric and magnetic contributions

\[ u_B = \frac{1}{2\mu_0} B^2 = \frac{1}{2} \varepsilon_0 E^2 = u_E \]

Instantaneous energy density

\[ u = u_E + u_B = \frac{1}{2\mu_0} B^2 + \frac{1}{2} \varepsilon_0 E^2 = 2u_E = \varepsilon_0 E^2 = 2u_B = \frac{1}{\mu_0} B^2 = \sqrt{\frac{\varepsilon_0}{\mu_0}} E B \]

Average & maximum energy densities

\[ \bar{u} = \varepsilon_0 E_{rms}^2 = \frac{1}{\mu_0} B_{rms}^2 = \sqrt{\frac{\varepsilon_0}{\mu_0}} E_{rms} B_{rms} \]

\[ = \frac{1}{2} u_{max} = \frac{1}{2} \varepsilon_0 E_{max}^2 = \frac{1}{2\mu_0} B_{max}^2 = \frac{1}{2} \sqrt{\frac{\varepsilon_0}{\mu_0}} E_{max} B_{max} \]
Remember: Exam #5 Runs thru Wed Dec. 4

Summary: power has a phase angle; transformers

Physics 220 Fall 2013 Course Assignment

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Hint: This is a good time to look at the formula sheet and the CS. NEW concept: displacement current. New circuit element: none.

New terms. Poynting Vector, Radiation pressure.

Student: I've heard rumors from the TA's that the final is not comprehensive. Is this true? If it is comprehensive, what are your suggestions on how to study everything we've learned in this course?

Rumor is false. Go back and work the exam questions and the sample exams in the packet.
Energy Flow (Poynting vector)

\[ \mathbf{S} \equiv \mathbf{E} \times \mathbf{H} = \mathbf{E} \times \frac{\mathbf{B}}{\mu_0} \]

Instantaneous Intensity (J/m\(^2\)/s):

\[ S = \frac{1}{\mu_0} EB = \frac{c}{\mu_0} B^2 = c \varepsilon_0 E^2 = cu \]

Average vs. Maximum Intensity:

\[ \bar{S} = cu = c \varepsilon_0 E_{rms}^2 = \frac{c}{\mu_0} B_{rms}^2 = \frac{1}{\mu_0} E_{rms} B_{rms} \]

\[ = \frac{1}{2} cu_{\text{max}} = \frac{1}{2} c \varepsilon_0 E_{\text{max}}^2 = \frac{c}{2 \mu_0} B_{\text{max}}^2 = \frac{1}{2 \mu_0} E_{\text{max}} B_{\text{max}} = \frac{1}{2} S_{\text{max}} \]
Energy Flow (Poynting vector)

\[ \vec{S} = c \vec{u} = c \varepsilon_0 E_{rms}^2 = \frac{c}{\mu_0} B_{rms}^2 = \frac{1}{\mu_0} E_{rms} B_{rms} \]

\[ = \frac{1}{2} c u_{max} = \frac{1}{2} c \varepsilon_0 E_{max}^2 = \frac{c}{2 \mu_0} B_{max}^2 = \frac{1}{2 \mu_0} E_{max} B_{max} = \frac{1}{2} S_{max} \]

Midday sunlight intensity is 900 W/m².

Average energy density (µJ/m³)?
(1) 1.5 (2) 3.0 (3) 4.5 (4) 6.0 (5) 9.0

Peak electric field (V/m)?
(1) 290 (2) 417 (3) 580 (4) 823 (5) 1164

RMS magnetic field (T)?
Radiation momentum and pressure

Light quanta have both energy and momentum: \( U = pc \)

Absorption: \( \Delta p = \frac{U}{c} \)

Reflection: \( \Delta p = 2\frac{U}{c} \)

\[
\text{pressure} = \frac{\text{force}}{\text{area}} = \frac{1}{A} \frac{\Delta p}{\Delta t} = \frac{1}{c} \frac{\Delta U}{A \Delta t}
\]

\( = \frac{S}{c} \) (absorption) or \( 2\frac{S}{c} \) (reflection)
iClicker Quiz

I have completed at least 50% of 34:6 and study-guide assignments associated with the lecture, as indicated on the course schedule.

A. True
B. False
Lab 12 due Wednesday.
Has any one figured out why power is sent to California DC?
A. the left (8)
B. to the right (5)
C. to the top (9)
D. to the bottom (8)
E. into the page (13)
F. out of the page (4)
G. none, because it is zero (3)

The Poynting vector indicates the direction of energy flow. Since the capacitor is discharging the energy is traveling from the capacitor to the inductor, so the Poynting vector is to the right. This can also be checked directly. \( \mathbf{S} \propto \mathbf{E} \times \mathbf{B} \). \( \mathbf{E} \) points toward the bottom of the page inside the circuit (high \( V \) down to low \( V \)) and \( \mathbf{B} \) points into the page (right-hand rule on the current): \( \mathbf{E} \times \mathbf{B} \) points to the right. The displacement current is continuous with the conduction current, so it is 3 A.
The radio station KSL broadcasts at a frequency of 1160 kHz and transmits 50 kW of average power. At a point 27 km west of the transmitter the electric field (rms) has magnitude $7F$ V/m (rms) (assume spherically symmetric outgoing waves and ignore energy absorption by the atmosphere). If, at a particular instant $\vec{E}$ at this location is vertically upward, then $\vec{B}$ at the same location points 8° (1) vertically upward (2) vertically downward (3) east (4) west (5) north (6) south (7) some other direction. The wave number, $k$, of the waves at this location has the value $9F$ SI units.

**Do we know enough to solve this problem?**

\[
S = \frac{P}{A} = \frac{P}{(4\pi r^2)} = \frac{(50 \times 10^3)}{[4\pi(27 \times 10^3)^2]} = 5.46 \times 10^{-6} \text{ W/m}^2.
\]

\[
E_{rms} = \sqrt{\frac{S_{avg}}{c\epsilon_0}} = \sqrt{\frac{(5.46 \times 10^{-6})}{(3 \times 10^8)(8.85 \times 10^{-12})}} = 4.53 \times 10^{-2} \text{ N/C}.
\]

West of the station, $E$ points up and $S$ points west. If $S = E \times B$, then $B$ must point north.

\[
k = \frac{\omega}{c} = \frac{2\pi f}{c} = \frac{2\pi(1160 \times 10^3)}{(3 \times 10^8)} = 0.024 \text{ m}.
\]
Reading quiz: According to the book what is the ideal length for each rod in an electric dipole antenna?

A. ¼ the wavelength
B. ½ the wavelength
C. 1/3 the wavelength
D. Equal to the wavelength
E. twice the wavelength

• Today: antennas and radiation. Use your chapter summaries.
Dipole antenna

Heinrich Rudolf Hertz
Lab 12 due Wednesday.
Has any one figured out why power is sent to California DC?
What is the ideal length for an end-fed car antenna tuned to FM 100? (1) 0.75 m (2) 1.5 m (3) 3 m (4) 6 m

\[ \lambda = \frac{c}{f} = \left( \frac{3 \times 10^8 \text{ m/s}}{1 \times 10^8 \text{ Hz}} \right) = 3 \text{ m} \]

\( \lambda/2 \) for center-fed antenna

\( \lambda/4 \) for end-fed antenna
Dipole radiation fields

\[ S \propto \sin^2(\theta) \]

http://www.falstad.com/mathphysics.html

Dipole radiation visualization link (MIT 8.02 course)
Rate the Tutors

If you used the physics tutorial lab this semester, we invite you to rate the tutors you received help from.

Rating form and photos of tutors:
http://gardner.byu.edu/tas/tutorrating.php

Also Rate the class: 0.5% ExtraCredit, if 80% of class rate class.

Student: Can we go over that question in class? Or maybe hold a review for the last exam?
Do the quizzes count of 2 points or the random point allocation on the online scores???? How come you never told us they were worth more than 2 points each??!!

Can you explain more about the Poynting vector in class?

Can we please go over problems like what we get on exams for the exam review instead of like the homework? It seems to me that would be more effective, as we can all just go to the TA lab if we want help on the homework, but can't necessarily guarantee that the TA's know how to do those.

Reviews for the final test?

Could you open the previous couple of warm up quizzes? I missed the one over thanksgiving break even though i did the reading.
Electric Dipole Source

Magnetic Dipole Source
Production of electromagnetic Waves by an Antenna

• Neither stationary charges nor steady currents can produce electromagnetic waves

• The fundamental mechanism responsible for this radiation is the acceleration of a charged particle

• Whenever a charged particle accelerates, it radiates energy
Production of em Waves by an Antenna, 2

- This is a *half-wave* antenna
- Two conducting rods are connected to a source of alternating voltage
- The length of each rod is one-quarter of the wavelength of the radiation to be emitted
Production of em Waves by an Antenna, 3

- The oscillator forces the charges to accelerate between the two rods
- The antenna can be approximated by an oscillating electric dipole
- The magnetic field lines form concentric circles around the antenna and are perpendicular to the electric field lines at all points
- The electric and magnetic fields are 90° out of phase at all times
- This dipole energy dies out quickly as you move away from the antenna
Production of EM Waves by an Antenna, final

- The source of the radiation found far from the antenna is the continuous induction of an electric field by the time-varying magnetic field and the induction of a magnetic field by a time-varying electric field.
- The electric and magnetic field produced in this manner are in phase with each other and vary as $1/r$.
- The result is the outward flow of energy at all times.
Radiative Resistance

IPP (Delta Utah): delivers 2 GW of 500 kV power to LA metro area

\[ R_{cable} = \rho \frac{l}{A} = \left(2.82 \times 10^{-8} \text{ } \Omega \cdot \text{cm} \right) \frac{(1000 \text{ km})}{\pi (4.25 \text{ mm})^2} = 500 \Omega \]

\[ I = \frac{V}{R_{cable}} = \frac{(500 \text{ kV})}{(500 \Omega)} = 1000 \text{ A} \]

\[ \lambda = \frac{c}{f} = \frac{(3 \times 10^{-8} \text{ m/s})}{(60 \text{ Hz})} = 5000 \text{ km} \quad \ell \approx 1000 \text{ km} = \frac{\lambda}{5} \]

\[ R_{\text{radiative}} = \frac{\pi}{12} \sqrt{\frac{\mu_0}{\varepsilon_0}} \left(\frac{\ell}{\lambda}\right)^2 = (100 \Omega) \left(\frac{\ell}{\lambda}\right)^2 = 4 \Omega \ll 500 \Omega \]
Final

• In the Testing Center
  – All next week M to F.
  – Wednesday 7am to 2pm here in the classroom. There will be a TA or I to answer questions. You will not wait out in the cold as you will at the TC.
  – I will probably take the Final at the:
    – A. classroom    B. TC.    C. toss up
Hardest Problems
33-1. An air-filled circular parallel plate capacitor with radius \( a = 5.00 \) cm and plate separation \( d = 2.00 \) mm, is driven by a 60 Hz alternating voltage with amplitude \( V = [01] \) ________ V. Naturally, the magnitude of the current is greatest at the instant when the voltage is zero. At such an instant, determine the magnitude of the (a) rate of change of electric flux in the capacitor, (b) displacement current in the capacitor, and (c) magnetic field near the edge of the capacitor. [(a) 100, 300 kV·m/s (b) 1.00, 3.00 \( \mu \)A (c) 5.00, 9.99 pT]
33-2. Which of the following laws or principles are required to solve the problems described below. In each case, choose only one answer. If more than one response seems appropriate, choose the one most fundamental to the problem at hand. Possible responses are: (1) Gauss’s law of electrostatics, (2) Gauss’s law of magnetism, (3) Faraday’s law, (4) Ampere-Maxwell law, (5) Lorentz force law.

(a) Determine the magnetic field near a current carrying wire.
(b) Determine the trajectory of a proton in a uniform magnetic field.
(c) Determine the electric field inside a charged capacitor.
(d) Determine the magnetic field inside a charging capacitor.
(e) Determine the power delivered by a wind-turbine generator.
(f) Determine the electric field near the surface of a conductor.
(g) Determine the voltage difference between the ends of a metal bar moving in a magnetic field.
(h) Determine the total magnetic flux through a closed surface.
(i) Determine the voltage in the secondary winding of a transformer.
(j) The magnetic field produced by a moving charged particle.
33-3. Determine the validity of each of the following statements. Possible responses are (1) True or (2) False.

(a) Ampere’s law is physically equivalent to the Lorentz force law.
(b) Gauss’s law of electrostatics is physically equivalent to Gauss’s law of magnetism.
(c) Coulomb’s law is physically equivalent to Gauss’s law of electrostatics.
(d) The Biot-Savart law is physically equivalent to Faraday’s law.
(e) Lenz’s law is a corollary of Faraday’s law.
(f) Gauss’s law of electrostatics relates electric charge to electric flux.
(g) Gauss’s law of magnetism relates magnetic charge to magnetic flux.
(h) The Ampere-Maxwell law relates magnetic circulation to changing electric flux.
(i) The Ampere-Maxwell law relates magnetic circulation to electric current.
(j) Faraday’s law relates electric charge to changing magnetic flux.
Complete this problem on a separate sheet of paper and submit it with your CID# prominently displayed.

Name and state each of Maxwell’s equations and the Lorentz force law in plain English with no reference to symbols or acronyms.
An electric dipole broadcasting antenna is placed on the positive y-axis at point A and is oriented vertically as shown. You are standing a long way from the broadcast antenna on the negative y-axis at point B. To receive the maximum signal on your radio, which is equipped with a long receiving antenna, your radio antenna should be oriented along the __10? (1) x-axis (2) y-axis (3) z-axis. If you have a magnetic dipole antenna (a current loop in the x-y plane), the axis of your receiving antenna should be oriented along __11? (same choices).

An electric dipole receiver antenna should be oriented parallel to the $E$ field, which is parallel to the electric dipole broadcasting antenna (along the z axis). $B$ must be perpendicular to both $E$ (z axis) and $S$ (y axis), and must therefore point along the x axis, which will be the optimal orientation of the magnetic dipole receiver.
**Summary:** power has a phase angle; transformers

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**Hint:** This is a good time to look at the formula sheet and the CS. **NEW concept:** displacement current. **New circuit element:** none.

**New terms.** Displacement current.

**I reopened warm-up exams for this exam thru Tuesday 11:00 pm.**