34.12 a. No. Since $\Delta V = -L \frac{dI}{dt}$ and ΔV and L are both known, we can only find $\frac{dI}{dt}$, not I. b. Yes, through the right-hand inductor, since $\left|\frac{dI}{dt}\right| = \frac{\Delta V}{L}$.

c. Yes, it is possible to tell: The current is decreasing. If $\frac{dI}{dt} < 0$ then $\Delta V_{\rm L} > 0$ and the input side is more negative, and the potential increases in the direction of the current.

34.16. Model: A changing magnetic field creates an electric field. Visualize:



Solve: (a) Apply Equation 34.26. For a point on the axis, r = 0 m, so E = 0 V/m. (b) For a point 2.0 cm from the axis,

$$E = \frac{r}{2} \left| \frac{dB}{dt} \right| = \left(\frac{0.020 \text{ m}}{2} \right) (4.0 \text{ T/s}) = 0.040 \text{ V/m}$$

34.19. Model: Assume that the current changes uniformly.

Visualize: We want to increase the current without exceeding a maximum potential difference. **Solve:** Since we want the minimum time, we will use the maximum potential difference:

$$\Delta V = -L\frac{dI}{dt} = -L\frac{\Delta I}{\Delta t} \Longrightarrow \Delta t = L \left| \frac{\Delta I}{\Delta V_{\text{max}}} \right| = (200 \times 10^{-3} \text{ H}) \frac{3.0 \text{ A} - 1.0 \text{ A}}{400 \text{ V}} = 1.0 \text{ ms}$$

Assess: If we change the current in any shorter time the potential difference will exceed the limit.

34.21. Visualize: The solenoid has inductance and when a current flows there is energy stored in the magnetic field.Solve: The inductance and energy of the solenoid are

$$L_{\text{sol}} = \frac{\mu_0 N^2 A}{l} = \frac{(4\pi \times 10^{-7} \text{ H/m})(200)^2 \pi (0.015 \text{ m})^2}{0.12 \text{ m}} = 2.96 \times 10^{-4} \text{ H}$$
$$U_{\text{L}} = \frac{1}{2} L I^2 = \frac{1}{2} (2.96 \times 10^{-4} \text{ H})(0.80 \text{ A})^2 = 9.5 \times 10^{-5} \text{ J}$$

34.25. Visualize: Please refer to Figure Ex34.25. This is a simple LR circuit if the resistors in parallel are treated as an equivalent resistor in series with the inductor.

Solve: We can find the equivalent resistance from the time constant since we know the inductance. We have

$$\tau = \frac{L}{R_{eq}} \Longrightarrow R_{eq} = \frac{L}{\tau} = \frac{3.6 \times 10^{-3} \text{ H}}{10 \times 10^{-6} \text{ s}} = 360 \Omega$$

The equivalent resistance is the parallel addition of the unknown resistor R and 600 Ω . We have

$$\frac{1}{R_{\rm eq}} = \frac{1}{600 \ \Omega} + \frac{1}{R} \Longrightarrow R = \frac{(600 \ \Omega)(360 \ \Omega)}{600 \ \Omega - 360 \ \Omega} = 900 \ \Omega$$

34.26. Visualize: Please refer to Figure Ex34.26. This is a simple LR circuit if the two resistors in series are treated as an equivalent resistor in series with the inductor. Solve: The time constant of the equivalent circuit is

$$\tau = \frac{L}{R_{\rm eq}} = \frac{L}{R_{\rm l} + R_{\rm 2}} = \frac{50 \times 10^{-3} \text{ H}}{500 \,\Omega} = 1.00 \times 10^{-4} \text{ s}$$

If the current is initially at the maximum, then it will decay exponentially with time according to $I(t) = I_0 e^{-t/\tau}$. The time $t_{1/2}$ when the current drops to half the initial value is found as follows:

$$\frac{1}{2}I_0 = I_0 e^{-t_{1/2}/\tau} \Longrightarrow \ln\left(\frac{1}{2}\right) = -t_{1/2}/\tau \Longrightarrow t_{1/2} = \tau \ln 2 = (1.00 \times 10^{-4} \text{ s})0.69 = 6.9 \times 10^{-5} \text{ s}$$

Assess: This is less than τ , as expected, since the time constant is the amount of time it takes to decay to 0.37 of the initial current and we are only going to 1/2. This result is quite general and is characteristic of all exponential decay phenomena.

34.59. Model: Use Faraday's law of electric induction. Visualize:



Equation 34.23, $\oint \vec{E} \cdot d\vec{s} = A \left| \frac{dB}{dt} \right|$, describes the relationship between an induced electric field and the flux

through a fixed area A. To solve this equation, choose a clockwise direction around a circle of radius r as the closed curve. The electric field vectors, as can be seen from the figure, are everywhere tangent to the curve. The line integral of \vec{E} then is

$$\oint \vec{E} \cdot d\vec{s} = (2\pi r)E$$

The direction of the induced electric field is chosen to agree with the right-hand rule applied to the flux calculation for magnetic field. Note that B = 0 outside the solenoid. **Solve:** Equation 34.23 now simplifies to

$$E(2\pi r) = \pi R^2 \frac{dB}{dt} \Longrightarrow E = \frac{R^2}{2r} \frac{dB}{dt}$$

Assess: At r = R, $E = \frac{1}{2}R dB/dt$, which is the same result as Equation 34.26.

34.76. Model: Assume negligible resistance in the *LC* part of the circuit.

Visualize: With the switch in position 1 for a long time the capacitor is fully charged. After moving the switch to position 2, there will be oscillations in the *LC* part of the circuit.

Solve: (a) After a long time the potential across the capacitor will be that of the battery and $Q_0 = C\Delta V_{\text{batt}}$. When the switch is moved, the capacitor will discharge through the inductor and *LC* oscillations will begin. The maximum current is

$$I_0 = \omega Q_0 = \omega C \Delta V_{\text{batt}} = \frac{C \Delta V_{\text{batt}}}{\sqrt{LC}} = \sqrt{\frac{C}{L}} \Delta V_{\text{batt}} = \sqrt{\frac{(2.0 \times 10^{-6} \text{ F})}{(50 \times 10^{-3} \text{ H})}} (12 \text{ V}) = 7.6 \times 10^{-2} \text{ A} = 76 \text{ mA}$$

(b) The current will be a maximum one-quarter cycle after the maximum charge. The period is

$$T = \frac{2\pi}{\omega} = 2\pi\sqrt{LC} = 2\pi\sqrt{(50 \times 10^{-3} \text{ H})(2.0 \times 10^{-6} \text{ F})} = 2.0 \text{ ms}$$

So the current is first maximum at $t_{\text{max}} = \frac{1}{4}T = 0.50$ ms.

34.78. Model: Assume an ideal inductor and an ideal (resistanceless) battery.

Visualize: Please refer to Figure P34.78. The current through the battery is the sum of the currents through the left and right branches of the circuit.

Solve: (a) Because the switch has been open a long time, no current is flowing the instant before the switch is closed. A basic property of an ideal inductor is that the current through it cannot change instantaneously. This is because the potential difference $\Delta V_{\rm L} = -L(dI/dt)$ would become infinite for an instantaneous change of current, and that is not physically possible. Because the current through the inductor was zero before the switch was closed, it must still be zero (or very close to it) immediately after the switch is closed. Conservation of current requires the current through the entire right branch to be the same as that through the inductor, so it is also zero immediately after the switch is closed. The only current is through the left 20 Ω resistor, which sees the full battery potential of the battery. Thus $I_{\rm bat} = I_{\rm left} = \Delta V_{\rm bat}/R = (10 \text{ V})/(20 \Omega) = 0.50 \text{ A}.$

(b) The current through the inductor increases as time passes. Once the current I_{right} reaches a steady value and is no longer changing, the potential difference across the inductor is $\Delta V_{\text{L}} = -L(dI/dt) = 0$ V. An ideal inductor has no resistance, so the inductor simply acts like a wire and has no effect on the circuit. The circuit is that of two 20 Ω resistors in parallel. The equivalent resistance is 10 Ω and the battery current is $I_{\text{bat}} = (10 \text{ V})/(10 \Omega) = 1.0 \text{ A}$.

34.79. Model: Assume an ideal inductor and an ideal (resistanceless) battery.

Visualize: Please refer to Figure P34.79.

Solve: (a) Because the switch has been open a long time, no current is flowing the instant before the switch is closed. A basic property of an ideal inductor is that the current through it cannot change instantaneously. This is because the potential difference $\Delta V_{\rm L} = -L(dI/dt)$ would become infinite for an instantaneous change of current, and that is not physically possible. Because the current through the inductor was zero before the switch was closed, it must still be zero (or very close to it) immediately after the switch is closed. Consequently, the inductor has no effect on the circuit. It is simply a 10 Ω resistor and 20 Ω resistor in series with the battery. The equivalent resistance is 30 Ω , so the current through the circuit (including through the 20 Ω resistor) is $I = \Delta V_{\rm bat}/R_{\rm eq} = (30 \text{ V})/(30 \Omega) = 1.0 \text{ A}.$

(b) After a long time, the currents in the circuit will reach steady values and no longer change. With steady currents, the potential difference across the inductor is $\Delta V_{\rm L} = -L(dI/dt) = 0$ V. An ideal inductor has no resistance ($R = 0 \Omega$), so the inductor simply acts like a wire. In this case, the inductor "shorts out" the 20 Ω resistor. All current from the 10 Ω resistor flows through the resistanceless inductor, so the current through the 20 Ω resistor is 0 A.

(c) When the switch has been closed a long time, and the inductor is shorting out the 20 Ω resistor, the current passing through the 10 Ω resistor and through the inductor is $I = (30 \text{ V})/(10 \Omega) = 3.0 \text{ A}$. Because the current through an inductor cannot change instantaneously, the current must remain 3.0 A immediately after the switch reopens. This current must go somewhere (conservation of current), but now the open switch prevents the current from going back to the battery. Instead, it must flow upward through the 20 Ω resistor. That is, the current flows *around* the *LR* circuit consisting of the 20 Ω resistor and the inductor. This current will decay with time, with time constant $\tau = L/R$, but immediately after the switch reopens the current is 3.0 A.

35.1. (a) Yes, up. Andre sees the same magnetic field as the laboratory field, which points up. (b) Andre sees an electric field $\vec{E}' = \vec{V} \times \vec{B}$, which by the right-hand rule points into the page.

35.2. (a) A magnetic force acting down and an electric force acting up. Sharon sees the same magnetic field as Bill but also sees an electric field $\vec{E}' = \vec{V} \times \vec{B}$. (Note that the magnetic and electric forces on the charge are equal and opposite so the total force on the charge is zero.)

(b) In Bill's frame of reference the charge is at rest and therefore has no magnetic force acting on it. Since there is not an electric field present in Bill's reference frame, no forces act on the charge.

35.4. Negative. The net current through the surface is to the right, and if you curl your fingers along the arrow around the surface, your thumb points to the left.

35.5. Decreasing. Pointing the thumb of your right hand makes your fingers curl ccw, so $\frac{d\Phi_e}{dt}$ must be negative to get a cw \vec{B} .

- **35.6.** (a) No. The direction of \vec{v}_{em} is $\vec{E} \times \vec{B}$ which would be along the -x-axis. (b) Yes. The Pointing vector requirement is satisfied.

- **35.7.** (a) The right-hand rule has $\vec{E} \times \vec{B}$ point out of the page. (b) $\vec{E} \times \vec{B}$ points up.

35.8. (a) Since $I \propto E_0^2$, the new intensity is 40 W/m².

(b) For an electromagnetic wave $E_0 \propto B_0$, so 40 W/m².

(c) For electromagnetic waves, doubling one amplitude requires that the other is doubled, so 40 W/m².
(d) Changing the frequency does not change the amplitudes and hence the intensity is unchanged at 10 W/m².

35.2. Model: Apply the Galilean transformation of fields.

Visualize: Please refer to Figure EX35.2.

Solve: (a) Equation 35.11 gives the Galilean field transformation equation for magnetic fields:

$$\vec{B}' = \vec{B} - \frac{1}{c^2}\vec{V} \times \vec{E}$$

 \vec{B} is in the positive \hat{k} direction, $\vec{B} = B\hat{k}$. For B' > B, $\vec{V} \times \vec{E}$ must be in the negative \hat{k} direction. Since $\vec{E} = E\hat{j}$,

 \vec{V} must be in the negative \hat{i} direction, so that $\vec{V} \times \vec{E} = -(\hat{V}\hat{i}) \times (\hat{E}\hat{j}) = -VE\hat{k}$. The rocket scientist will measure B' > 0

B, if the rocket moves along the -x-axis.

(b) For B' = B, $\vec{V} \times \vec{E}$ must be zero. The rocket scientist will measure B' = B if the rocket moves along either the +y-axis or the -y-axis.

(c) For B' < B, $\vec{V} \times \vec{E}$ must be in the positive \hat{k} direction. The rocket scientist will measure B' < B, if the rocket moves along the +x-axis.

35.4. Model: Use the Galilean transformation of fields.

Visualize: Please refer to Figure EX35.4. We are given $\vec{V} = 2.0 \times 10^6 \hat{i}$ m/s, $B' = 1.0 \hat{j}$ T, and $\vec{E}' = 1.0 \times 10^6 \hat{k}$ V/m.

Solve: Equation 35.11 gives the Galilean transformation equations for the electric and magnetic fields in S and S' frames:

$$\vec{E} = \vec{E}' - \vec{V} \times \vec{B}' \qquad \vec{B} = \vec{B}' + \frac{1}{c^2} \vec{V} \times \vec{E}'$$

The electric and magnetic fields viewed from earth are

$$\vec{E} = 1.0 \times 10^6 \,\hat{k} \,\,\text{V/m} - \left(2.0 \times 10^6 \,\hat{i} \,\,\text{m/s}\right) \times \left(1.0 \,\hat{j} \,\,\text{T}\right) = -\left(1.0 \times 10^6 \,\,\text{V/m}\right) \hat{k}$$

$$\vec{B} = 1.0\hat{j} \text{ T} + \frac{1}{c^2} \left(2.0 \times 10^6 \hat{i} \text{ m/s} \right) \times \left(1.0 \times 10^6 \hat{k} \text{ V/m} \right) = 1.0\hat{j} \text{ T} - \frac{2.0 \times 10^{12} \text{ V/m}}{\left(3.0 \times 10^8 \text{ m/s} \right)^2} \hat{j} = 0.99998 \hat{j} \text{ T}$$

Assess: Although B < B', you need 5 significant figures of accuracy to tell the difference between them.

35.5. Model: Use the Galilean transformation of fields.

Visualize: Please refer to Figure EX35.5. We are given $\vec{V} = 1.0 \times 10^6 \hat{i}$ m/s, $\vec{B} = 0.50 \hat{k}$ T, and $\vec{E} = \left(\frac{1}{\sqrt{2}}\hat{i} + \frac{1}{\sqrt{2}}\hat{j}\right) \times 10^6$ V/m.

Solve: Equation 35.11 gives the Galilean transformation equation for the electric field in the S and S' frames: $\vec{E}' = \vec{E} + \vec{V} \times \vec{B}$. The electric field from the moving rocket is

$$\vec{E}' = (\hat{i} + \hat{j})0.707 \times 10^6 \text{ V/m} + (1.0 \times 10^6 \hat{i} \text{ m/s}) \times (0.50 \hat{k} \text{ T}) = (0.707 \times 10^6 \hat{i} + 0.207 \times 10^6 \hat{j}) \text{ V/m}$$
$$\theta = \tan^{-1} \left(\frac{0.207 \times 10^6 \text{ V/m}}{0.707 \times 10^6 \text{ V/m}} \right) = 16.3^\circ \text{ above the } x \text{ 4axis}$$

35.8. Solve: The displacement current is defined as $I_{disp} = \varepsilon_0(d\Phi_e/dt)$. The electric flux inside a capacitor with plate area *A* is $\Phi_e = EA$. The electric field inside a capacitor is $E = \eta/\varepsilon_0 = (Q/A)/\varepsilon_0$, and thus the electric flux is

$$\Phi_{\rm e} = EA = \frac{Q}{\varepsilon_0} = \frac{CV_{\rm C}}{\varepsilon_0}$$

where $V_{\rm C}$ is the capacitor voltage. The capacitance C is constant, hence the displacement current is

$$I_{\rm disp} = \varepsilon_0 \frac{d\Phi_{\rm e}}{dt} = \varepsilon_0 \frac{d}{dt} \left(\frac{CV_{\rm C}}{\varepsilon_0}\right) = C \frac{dV_{\rm C}}{dt}$$

35.10. Model: The electric field inside a parallel-plate capacitor is uniform. As the capacitor is charged, the changing electric field induces a magnetic field.

Visualize: The induced magnetic field lines are circles concentric with the capacitor. Please refer to Figure 35.18.

Solve: (a) The Ampere-Maxwell law is

$$\oint \vec{B} \cdot d\vec{s} = \varepsilon_0 \mu_0 \frac{d\Phi_e}{dt} = \varepsilon_0 \mu_0 A \frac{dE}{dt}$$

where *EA* is the electric flux through the circle of radius *r*. The magnetic field is everywhere tangent to the circle of radius *r*, so the integral of $\vec{B} \cdot d\vec{s}$ around the circle is simply $B(2\pi r)$. The Ampere-Maxwell law becomes

$$2\pi rB = \varepsilon_0 \mu_0 \left(\pi r^2\right) \frac{dE}{dt} \Longrightarrow B = \varepsilon_0 \mu_0 \frac{r}{2} \frac{dE}{dt}$$

On the axis, r = 0 m, so B = 0 T. (b) At r = 3.0 cm,

$$B = \frac{1}{(3.0 \times 10^8 \text{ m/s})^2} \left(\frac{0.030 \text{ m}}{2}\right) (1.0 \times 10^6 \text{ V/m s}) = 1.67 \times 10^{-13} \text{ T}$$

(c) For r > 5.0 cm, the electric flux Φ_e is the flux through a 10-cm-diameter circle because E = 0 V/m outside the capacitor plates. The Ampere-Maxwell law is

$$B(2\pi r) = \varepsilon_0 \mu_0 \pi R^2 \frac{dL}{dt}$$

$$\Rightarrow B = \varepsilon_0 \mu_0 \frac{R^2}{2r} \frac{dE}{dt} = \frac{1}{\left(3.0 \times 10^8 \text{ m/s}\right)^2} \frac{\left(0.050 \text{ m}\right)^2}{2\left(0.07 \text{ m}\right)} \left(1.0 \times 10^6 \text{ V/m s}\right) = 1.98 \times 10^{-13} \text{ T}$$

35.14. Model: Electromagnetic waves are sinusoidal. Solve: (a) The magnetic field is $B_z = B_0 \sin(kx - \omega t)$, where $B_0 = 3.00 \ \mu T$ and $k = 1.00 \times 10^7 \text{ m}^{-1}$. The wavelength is

$$\lambda = \frac{2\pi}{k} = \frac{2\pi}{1.00 \times 10^7 \text{ m}^{-1}} = 6.28 \times 10^{-7} \text{ m} = 628 \text{ nm}$$

(b) The frequency is

$$f = \frac{c}{\lambda} = \frac{3.0 \times 10^8 \text{ m/s}}{6.28 \times 10^{-7} \text{ m}} = 4.77 \times 10^{14} \text{ Hz}$$

(c) The electric field amplitude is

is

$$E_0 = cB_0 = (3 \times 10^8 \text{ m/s})(3.00 \times 10^{-6} \text{ T}) = 900 \text{ V/m}$$

35.31. Model: Use the Galilean transformation of fields. Assume that the electric and magnetic fields are uniform inside the capacitor.

Visualize: Please refer to Figure P35.31. The laboratory frame is the S frame and the proton's frame is the S' frame.

Solve: (a) The electric field is directed downward, and thus the electric force on the proton is downward. The magnetic field \vec{B} is oriented so that the force on the proton is directed upward. Use of the right-hand rule tells us that the magnetic field is directed into the page. The magnitude of the magnetic field is obtained from setting the magnetic force equal to the electric force, yielding the equation evB = eE. Solving for *B*,

$$B = \frac{E}{v} = \frac{1.0 \times 10^5 \text{ V/m}}{1.0 \times 10^6 \text{ m/s}} = 0.10 \text{ T}$$

Thus $\vec{B} = (0.10 \text{ T}, \text{ into page}).$

(b) In the S' frame, the magnetic and electric fields are

$$\vec{B}' = \vec{B} - \frac{1}{c^2} \vec{V} \times \vec{E} = -0.10\hat{k} \text{ T} - \frac{\left(1.0 \times 10^6 \,\hat{j} \text{ m/s}\right) \times \left(1.0 \times 10^5 \,\hat{i} \text{ V/m}\right)}{\left(3.0 \times 10^8 \text{ m/s}\right)^2} \approx -0.10\hat{k} \text{ T}$$
$$\vec{E}' = \vec{E} + \vec{V} \times \vec{B} = 1.0 \times 10^5 \hat{i} \frac{\text{V}}{\text{m}} + \left(1.0 \times 10^6 \,\hat{j} \text{ m/s}\right) \times \left(-0.10\hat{k} \text{ T}\right) = 0 \frac{\text{V}}{\text{m}}$$

(c) There is no electric force in the proton's frame because E' = 0, and there is no magnetic force because the proton is at rest in the S' frame.

35.33. Model: Use the Galilean transformation of fields. Visualize:



View from left end

A current of 2.5 A flows to the right through the wire, and the plastic insulation has a charge of linear density $\lambda =$

2.5 n C/cm.

Solve: The magnetic field B at a distance r from the wire is

$$\vec{B} = \left(\frac{\mu_0 I}{2\pi r}, \text{ clockwise seen from left}\right)$$

On the other hand, \vec{E} is radially out along \hat{r} , that is,

$$\vec{E} = \frac{\lambda}{2\pi\varepsilon_0 r} \hat{r}$$

As the mosquito is 1.0 cm from the center of the wire at the top of the wire,

$$B = \frac{(4\pi \times 10^{-7} \text{ T m/A})(2.5 \text{ A})}{2\pi (0.010 \text{ m})} = 5.0 \times 10^{-5} \text{ T}$$
$$E = \frac{(2.5 \times 10^{-7} \text{ C/m})(2)(9.0 \times 10^9 \text{ N m}^2/\text{C}^2)}{0.010 \text{ m}} = 4.5 \times 10^5 \frac{\text{V}}{\text{m}}$$

where the direction of \vec{B} is out of the page and the direction of \vec{E} is radially outward. In the mosquito's frame (let us call it S'), we want $\vec{B}' = \vec{0}$ T. Thus,

$$\vec{B}' = \vec{B} - \frac{1}{c^2}\vec{V} \times \vec{E} = 0 \implies \vec{B} = \frac{1}{c^2}\vec{V} \times \vec{E}$$

Because $\vec{V} \times \vec{E}$ must be in the direction of \vec{B} and \vec{E} is radially outward, according to the right-hand rule \vec{V} must be along the direction of the current. The magnitude of the velocity is

$$V = \frac{c^2 B}{E} = \frac{\left(3.0 \times 10^8 \text{ m/s}\right)^2 \left(5.0 \times 10^{-5} \text{ T}\right)}{4.5 \times 10^5 \text{ V/m}} = 1.0 \times 10^7 \text{ m/s}$$

The mosquito must fly at 1.0×10^7 m/s parallel to the current. This is highly unlikely to happen unless the mosquito is from Planet Krypton, like Superman.

35.35. Model: Use Faraday's law of electric induction and assume that the magnetic field inside the solenoid is uniform.

Visualize:



Equation 35.17 for Faraday's law is

$$\oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_{\rm m}}{dt} = -\frac{d}{dt} \left[\int \vec{B} \cdot d\vec{A} \right]$$

To solve this equation, choose a *clockwise* direction around a circle of radius r as the closed curve. The electric field vectors, as the figure shows, are everywhere tangent to the curve. The line integral of \vec{E} then is

$$\oint \vec{E} \cdot d\,\vec{s} = E(2\pi r)$$

To do the surface integral, we need to know the sign of the flux or the integral $\int \vec{B} \cdot d\vec{A}$. Curl your right fingers around the circle in the clockwise direction. Your thumb points to the right, which is along the same direction as the magnetic field \vec{B} . That is, $\int \vec{B} \cdot d\vec{A} = B\pi r^2$ is positive.

Solve: (a) Since $B = 10.0 \text{ T} + (2.0 \text{ T}) \sin[2\pi (10 \text{ Hz})t]$, Faraday's law simplifies to

$$E(2\pi r) = -\pi r^2 \frac{dB}{dt} = -\pi r^2 (2.0 \text{ T}) [2\pi (10 \text{ Hz})] \cos [2\pi (10 \text{ Hz})t] \Rightarrow E = -\left(20.0 \frac{\text{V}}{\text{m}^2}\right) \pi r \cos [2\pi (10 \text{ Hz})t]$$

The field strength is maximum when the cosine function is equal to -1. Hence at r = 1.5 cm,

$$E_{\rm max} = \left(20.0 \ \frac{\rm V}{\rm m^2}\right) \pi \left(0.015 \ {\rm m}\right) = 0.94 \ {\rm V/m}$$

(b) E is maximum when $\cos[2\pi(10 \text{ Hz})t] = -1$ which means when $\sin[2\pi(10 \text{ Hz})t] = 0$. Under this condition,

$$B = (10.0 \text{ T}) + (2.0 \text{ T}) \sin [2\pi (10 \text{ Hz})t] = 10.0 \text{ T}$$

That is, B = 10.0 T at the instant *E* has a maximum value of 0.94 V/m.

35.38. Model: Assume the electric field inside the capacitor is uniform and use the Ampere-Maxwell law. Visualize:



Solve: (a) For a current-carrying wire, Example 33.3 yields an equation for the magnetic field strength:

$$B = \frac{\mu_0 I_{\text{wire}}}{2\pi r} = \frac{\left(4\pi \times 10^{-7} \text{ T m/A}\right)\left(10 \text{ A}\right)}{\left(2\pi\right)\left(2.0 \times 10^{-3} \text{ m}\right)} = 1.0 \times 10^{-3} \text{ T}$$

(b) Example 35.3 found that the induced magnetic field inside a charging capacitor is

$$B = \frac{\mu_0}{2\pi} \frac{r}{R^2} \frac{dQ}{dt} = \frac{\mu_0}{2\pi} \frac{r}{R^2} I_{\text{wire}}$$

where we used $I_{\text{wire}} = dQ/dt$ as the actual current in the wire leading to the capacitor. At r = 2.0 mm,

$$B = \frac{(4\pi \times 10^{-7} \text{ T m/A})(2.0 \times 10^{-3} \text{ m})}{2\pi (5.0 \times 10^{-3} \text{ m})^2} (10 \text{ A}) = 1.60 \times 10^{-4} \text{ T}$$

35.40. Model: Assume that the electric field inside the cylinder is uniform. Use the Ampere-Maxwell law to obtain the induced magnetic field. Visualize:



Solve: (a) The electric flux through the entire cylinder is $\Phi = \int \vec{E} \cdot d\vec{A}$. For a closed curve of radius *R*, assuming a clockwise direction around the ring, the right-hand rule places the thumb into the page, which is the same direction as that of the electric field \vec{E} . Thus, we will take the flux Φ to have a positive sign:

$$\Phi = E(\pi R^2) = \left(1.0 \times 10^8 t^2 \ \frac{\text{V}}{\text{m}}\right) \left[\pi \left(3.0 \times 10^{-3} \ \text{m}\right)^2\right] = \left(2.8 \times 10^3 t^2\right) \text{Vm}$$

(b) From the Ampere-Maxwell law, with $I_{\text{through}} = 0$,

$$\oint \vec{B} \cdot d\vec{s} = \varepsilon_0 \mu_0 \frac{d\Phi_e}{dt} = \varepsilon_0 \mu_0 \frac{d\Phi_e}{dt}$$

Because Φ_e is positive and the field strength increases with time, $d\Phi_e/dt$ is positive. The line integral is therefore positive, which means that *B* is in the clockwise direction. This reasoning applies to both the r < R and r > R regions. Thus the field lines are clockwise and they are shown in the figure.

(c) We can now make use of the Ampere-Maxwell law to find the magnitude of *B* for r < R. Based upon parts (a) and (b),

$$B(2\pi r) = \varepsilon_0 \mu_0 \frac{dE}{dt} (\pi r^2) \Rightarrow B = \varepsilon_0 \mu_0 \left(\frac{r}{2}\right) \frac{dE}{dt} = \frac{r}{2c^2} \left[\left(1.0 \times 10^8 \ \frac{V}{m}\right) 2t \right] = \left(1.11 \times 10^{-9} \ rt\right) T$$

where r is in m and t is in s.

At r = 2 mm and t = 2.0 s,

$$B = (1.11 \times 10^{-9})(2.0 \times 10^{-3})(2.0)$$
 T = 4.4×10⁻¹² T

(d) For r > R, the flux is confined to a circle of radius R. Thus

$$B(2\pi r) = \varepsilon_0 \mu_0 \left(\frac{dE}{dt}\right) \pi R^2 \Longrightarrow B = \frac{R^2}{2c^2 r} \left[\left(1.0 \times 10^8 \ \frac{\mathrm{V}}{\mathrm{m}}\right) 2t \right] = \left(1.00 \times 10^{-14} \ \frac{t}{r}\right) \mathrm{T}$$

where r is in m and t is in s.

At
$$r = 4.0$$
 mm and $t = 2.0$ s,

$$B = \frac{1.00 \times 10^{-14} (2.0)}{(4.0 \times 10^{-3})} \text{ T} = 5.0 \times 10^{-12} \text{ T}$$

35.42. Solve: (a) The electric field energy density is $u_E = \frac{1}{2} \varepsilon_0 E^2$ and the magnetic field energy density is $u_B = (1/2\mu_0)B^2$. In an electromagnetic wave, the fields are related by E = cB. Using this and the fact that $c^2 = 1/(\varepsilon_0\mu_0)$, we find

$$u_{\rm E} = \frac{\varepsilon_0}{2} E^2 = \frac{\varepsilon_0}{2} (cB)^2 = \frac{c^2 \varepsilon_0}{2} B^2 = \frac{\varepsilon_0}{2\varepsilon_0 \mu_0} B^2 = \frac{1}{2\mu_0} B^2 = u_{\rm B}$$

(b) Since the energy density is equally divided between the electric field and the magnetic field, the total energy density in an electromagnetic wave is $u_{\text{tot}} = u_{\text{E}} + u_{\text{B}} = 2u_{\text{E}}$. We also know that the wave intensity is $I = \frac{1}{2} c \varepsilon_0 E_0^2$. Thus

$$u_{\text{tot}} = 2u_{\text{E}} = \varepsilon_0 E_0^2 = \frac{2}{c} \left(\frac{1}{2} c \varepsilon_0 E_0^2 \right) = \frac{2I}{c} = \frac{2(1000 \text{ W/m}^2)}{3.0 \times 10^8 \text{ m/s}} = 6.67 \times 10^{-6} \text{ J/m}^3$$

35.45. Model: The microwave beam is an electromagnetic wave. The water does not lose heat during the process.

Solve: The rate of energy transfer from the beam to the cube is

$$P = (0.80)IA = (0.80)\frac{C\varepsilon_0}{2}E_0^2A$$

= $(0.80)\frac{(3 \times 10^8 \text{ m/s})(8.85 \times 10^{-12} \text{ C}^2/\text{Nm}^2)}{2}(11 \times 10^3 \text{ V/m})^2(0.10 \text{ m})^2 = 1.29 \text{ kW}$

The amount of energy required to raise the temperature by 50 °C is

$$\Delta E = mc\Delta T = (0.10 \text{ m})^3 (1000 \text{ kg/m}^3) (4186 \text{ J/kg/}^\circ\text{C}) (50 \text{ C}) = 2.09 \times 10^5 \text{ J}$$

The time required for the water to absorb this much energy from the microwave beam is

$$\Delta t = \frac{\Delta E}{P} = \frac{2.09 \times 10^5 \text{ J}}{1.29 \times 10^3 \text{ W}} = 162 \text{ s}$$

Assess: Raising 1 kg of water by 50°C in a microwave oven takes around 2–3 minutes, so this is reasonable.

35.49. Model: The laser beam is an electromagnetic wave.Solve: The maximum intensity of the laser beam is determined by the maximum electric field strength in air. Thus the maximum power delivered by the beam is

$$P = IA = \frac{c\varepsilon_0}{2} E_0^2 A$$

= $\frac{(3 \times 10^8 \text{ m/s})(8.85 \times 10^{-12} \text{ C}^2/\text{Nm}^2)}{2} (3.0 \times 10^6 \text{ V/m})^2 \pi (0.050 \text{ m})^2$
= $9.4 \times 10^7 \text{ W/m}^2$