PH 220

Lance Nelson

Inductors

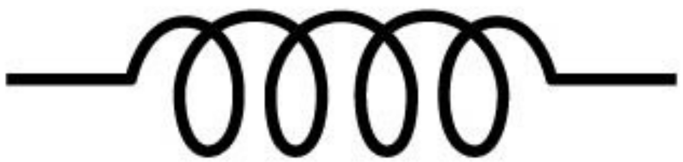
a. Capacitors store energy in the form of an electric field.
b. Resistors dissipate thermal energy.
c. Inductors store energy in the form of a magnetic field.

Inductance

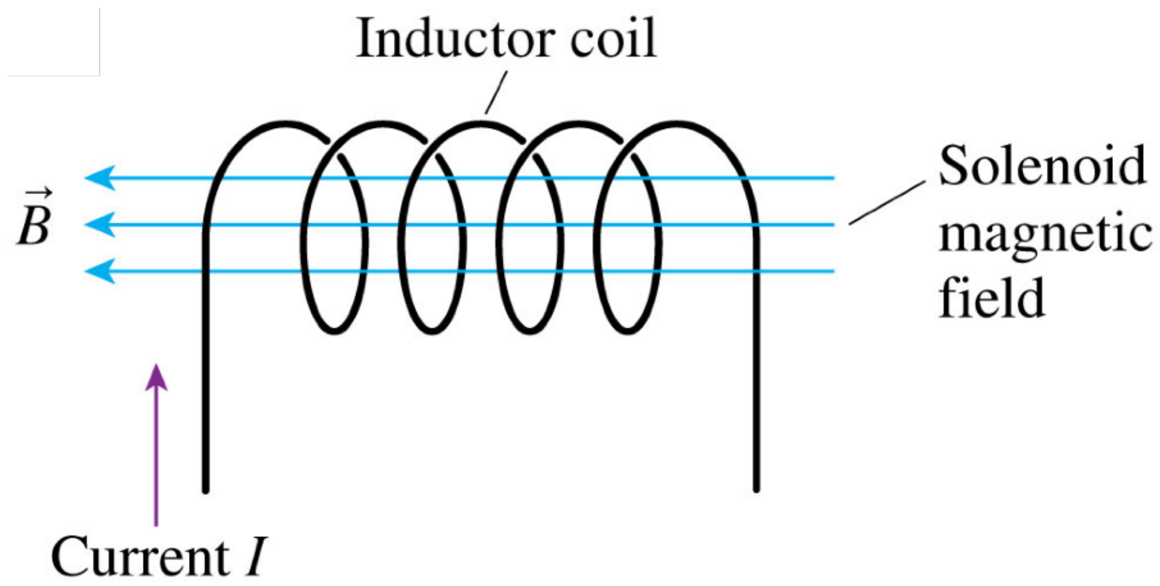
$$L_{\text{solenoid}} = \frac{\Phi_{\text{m}}}{I} = \frac{\mu_0 N^2 A}{l}$$

- The SI unit of inductance is the henry, defined as:

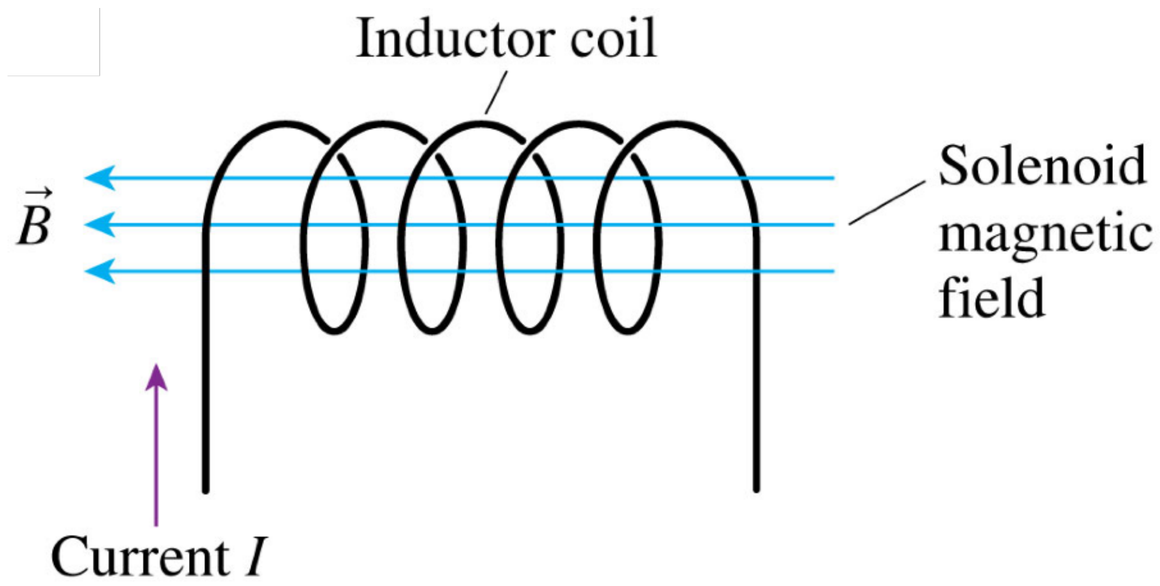
  1 henry = 1 H = 1 Wb/A = 1 T m2/A



Inductors

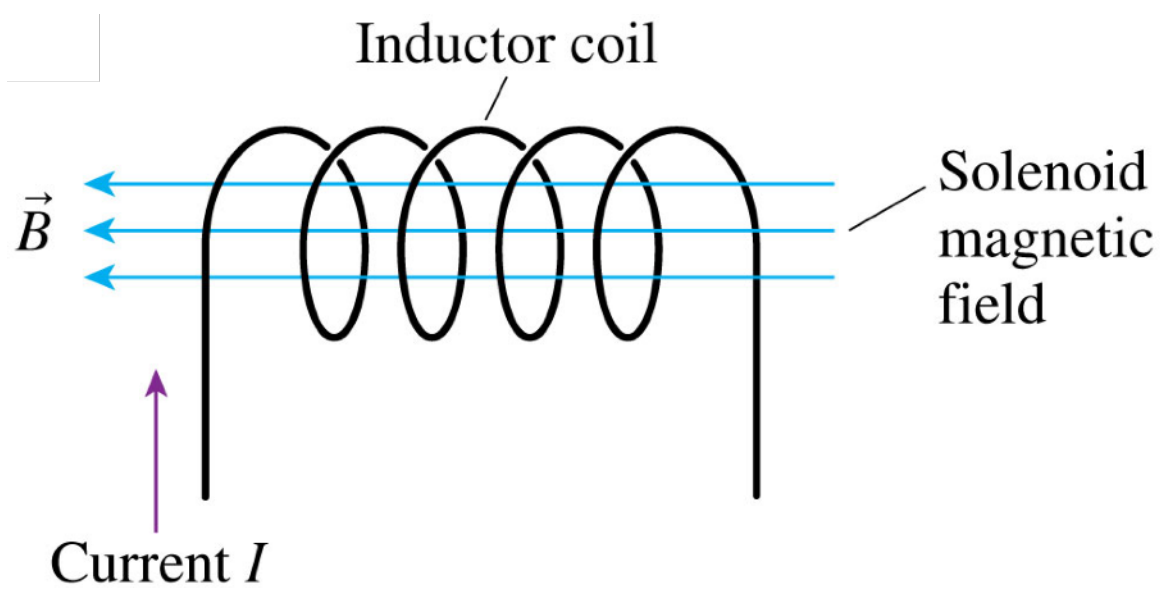


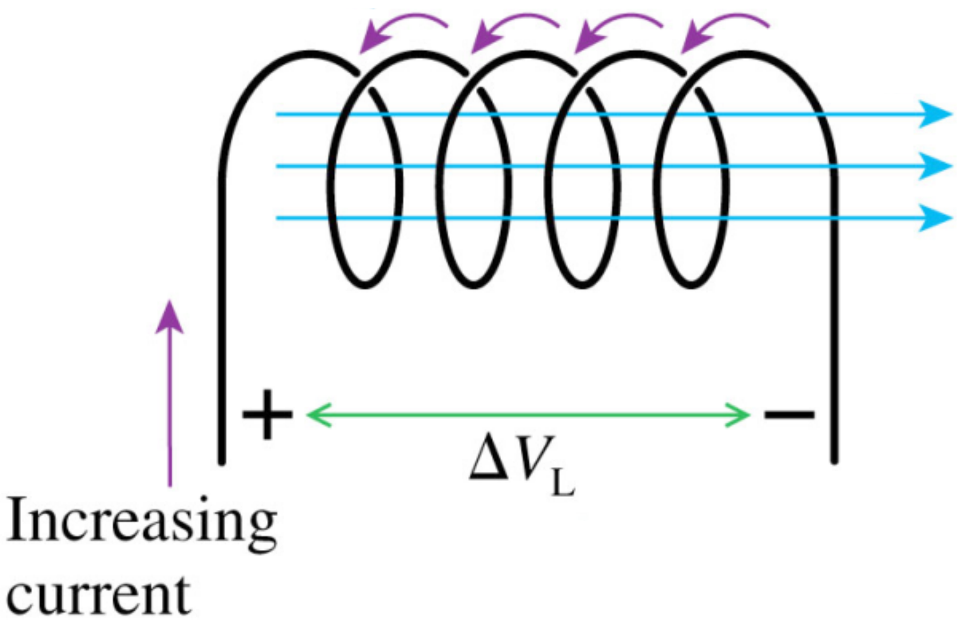
Inductors



What if I steadily increase the current? What will happen?

Inductors





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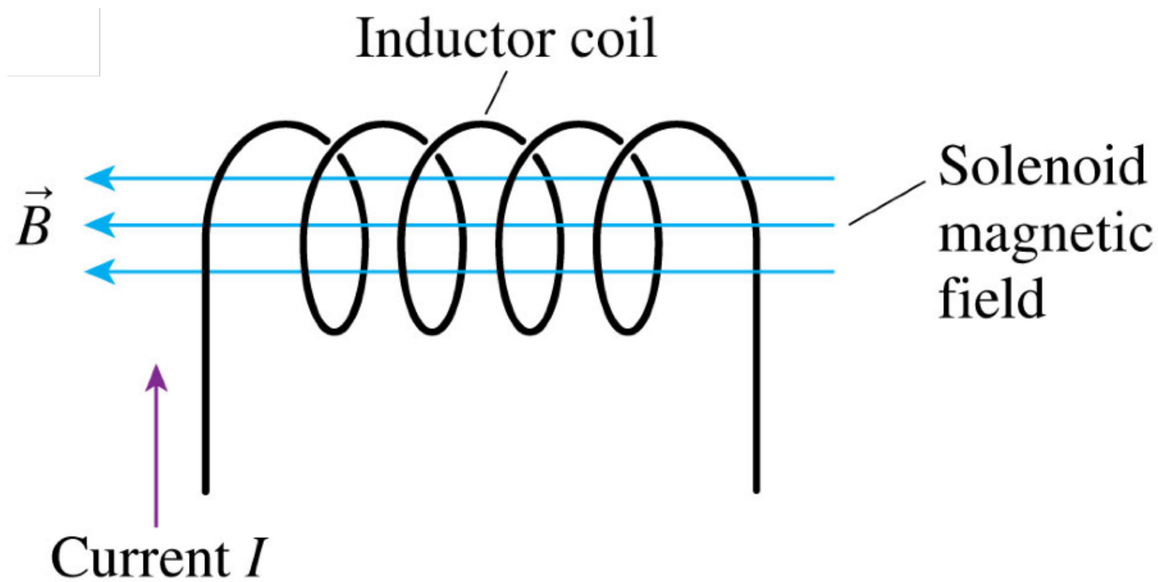
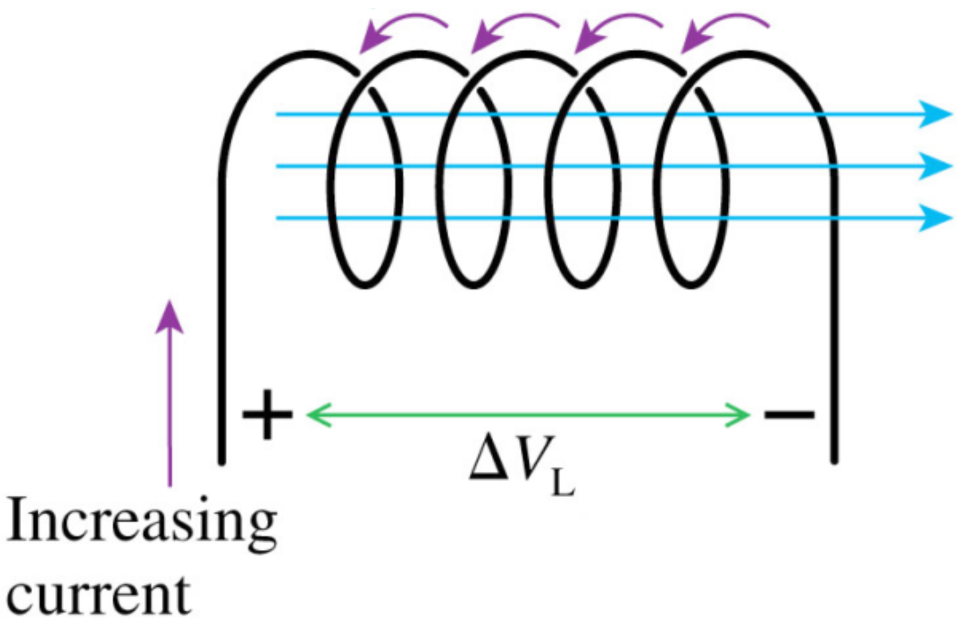
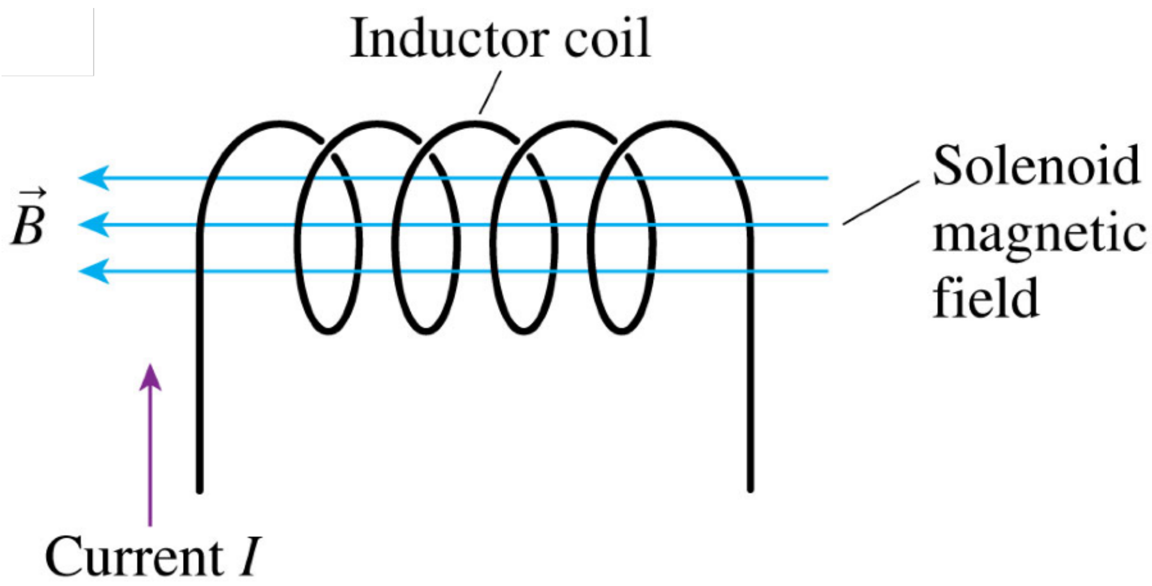
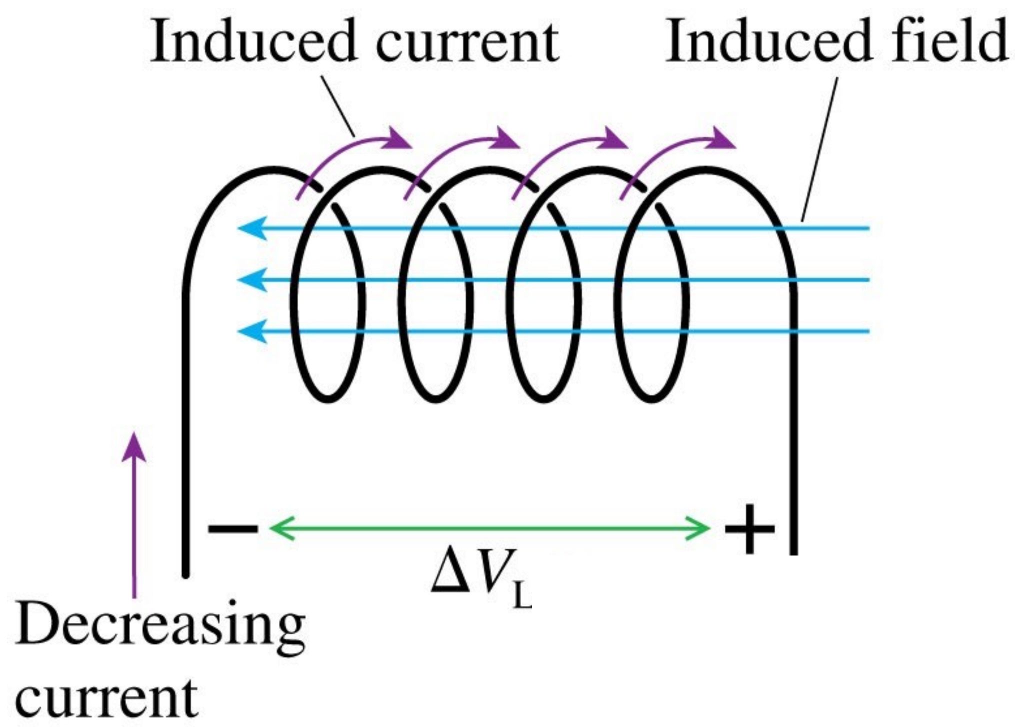




What if I steadily decrease the current? What will happen?

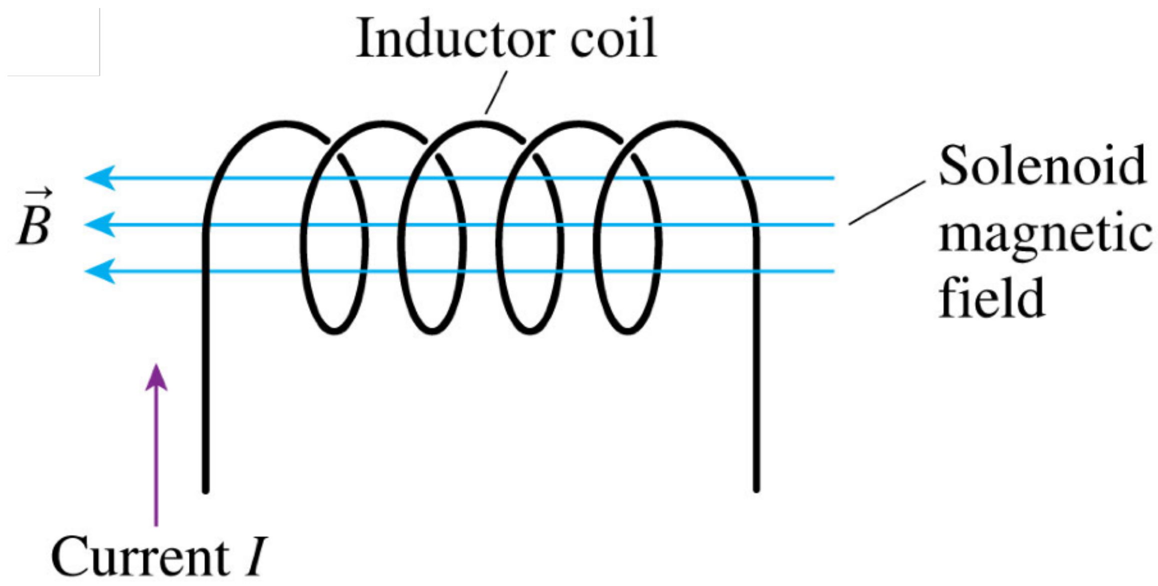
Inductors

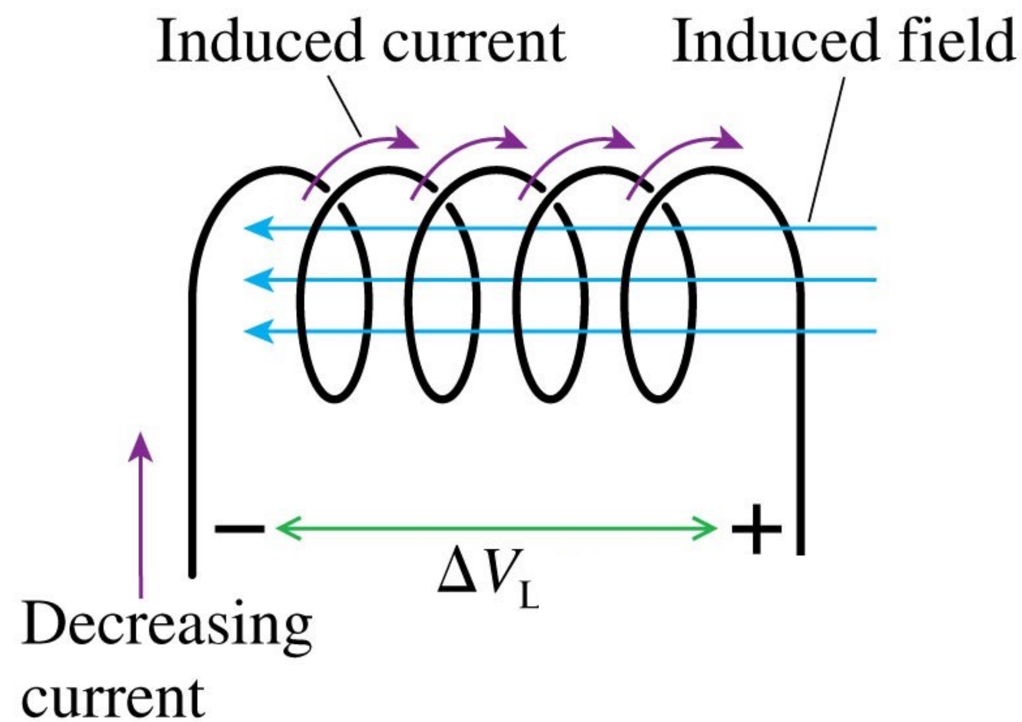




What if I steadily decrease the current? What will happen?

Inductors

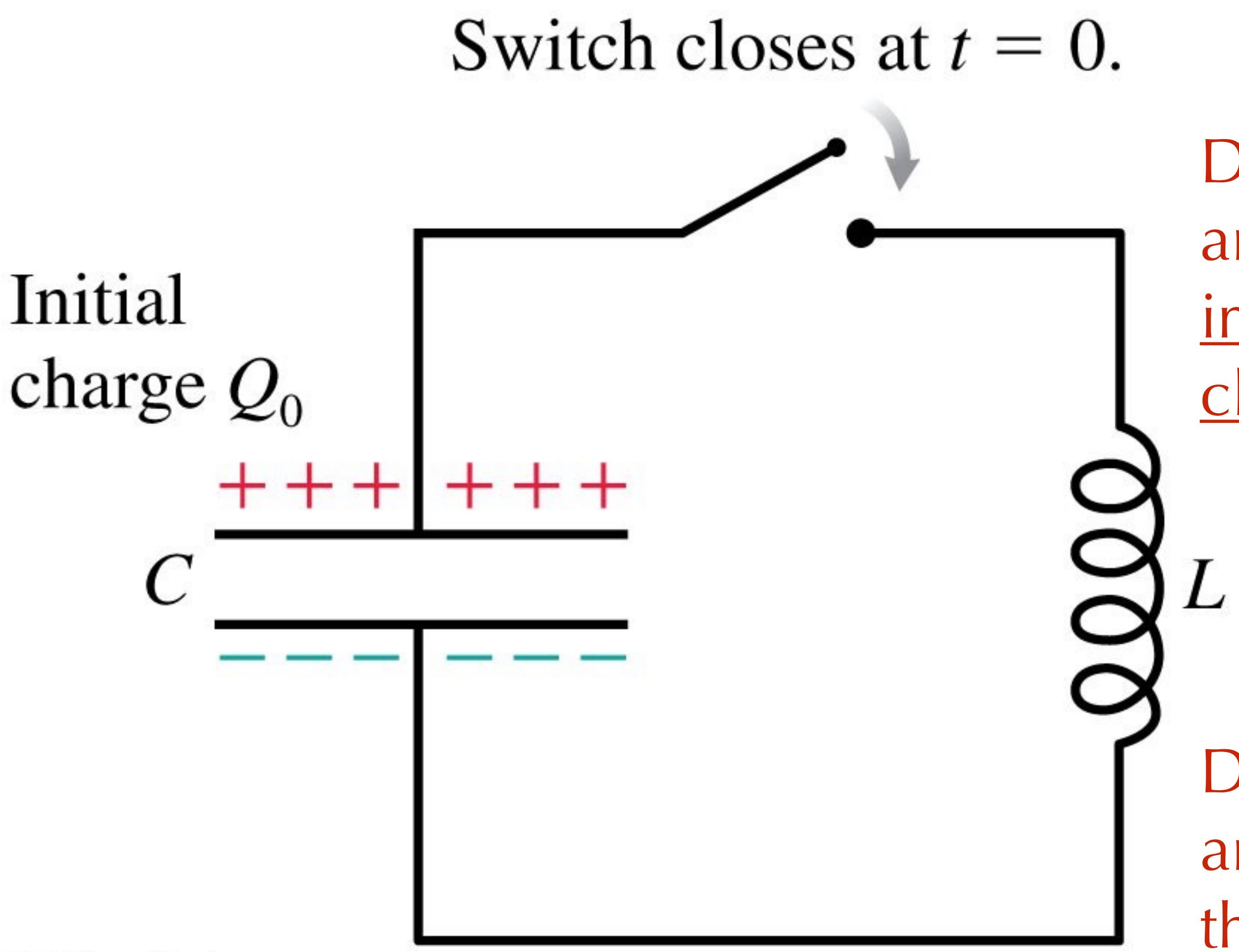




What if I steadily decrease the current? What will happen?

$$\Delta V_L = -L\frac{dI}{dt}$$

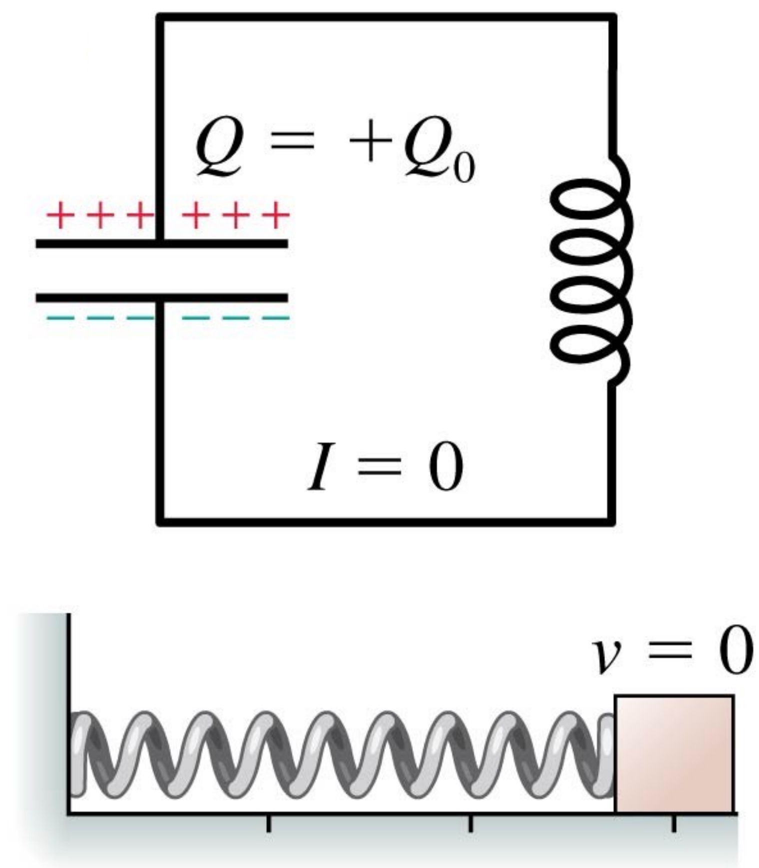
LC circuits



Describe the current in the circuit and voltages across each element <u>immediately after the switch is closed</u>.

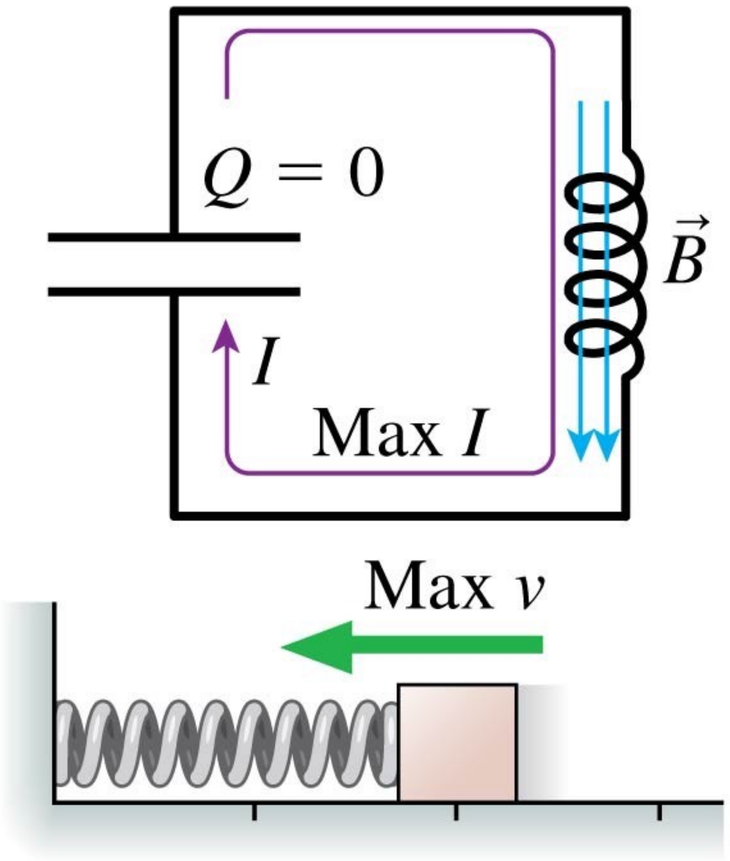
Describe the current in the circuit and voltages across each element <u>at the moment when the capacitor has no charge on it</u>.

An analogy



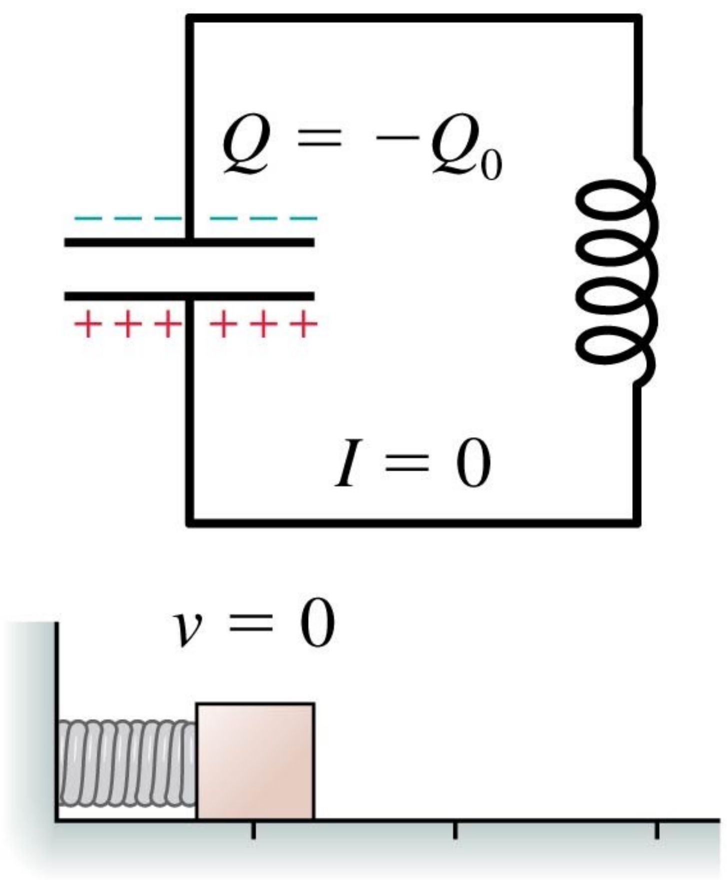
Maximum capacitor charge is like a fully stretched spring.

An analogy

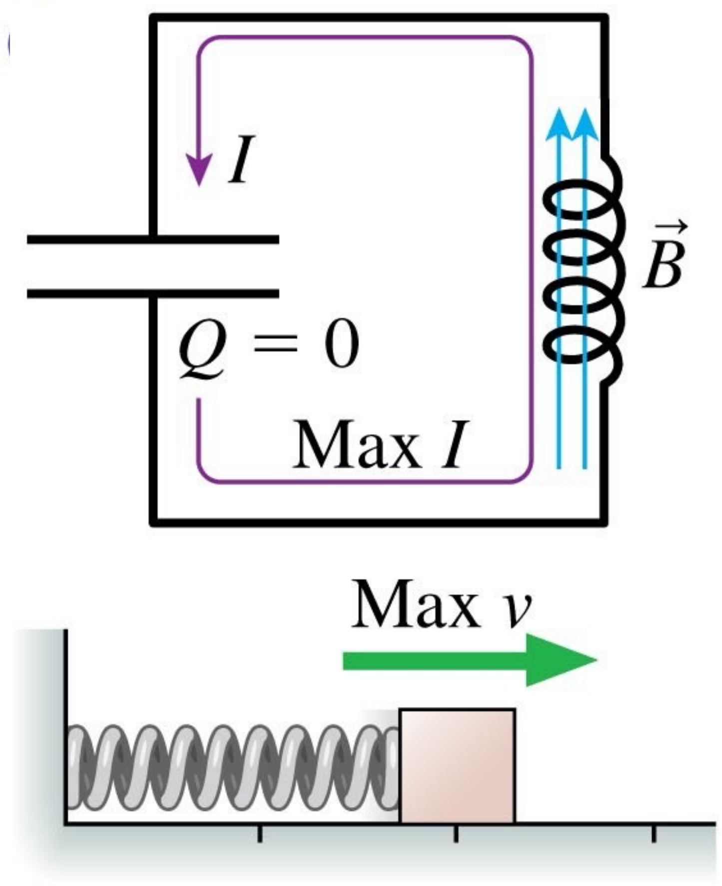


Maximum current is like the block having maximum speed.

An analogy



An analogy



Now the math…

$$\Delta V_C + \Delta V_L = 0$$

Now the math…

$$\Delta V_C + \Delta V_L = 0$$

$$\frac{Q}{C} - L\frac{dI}{dt} = 0$$

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$$I = -\frac{dQ}{dt}$$

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$$\frac{Q}{C} - L\frac{d}{dt}(-\frac{dQ}{dt}) = 0$$

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$$\frac{Q}{C} + L\frac{d^2Q}{dt^2} = 0$$

Now the math…

$$\Delta V_C + \Delta V_L = 0$$

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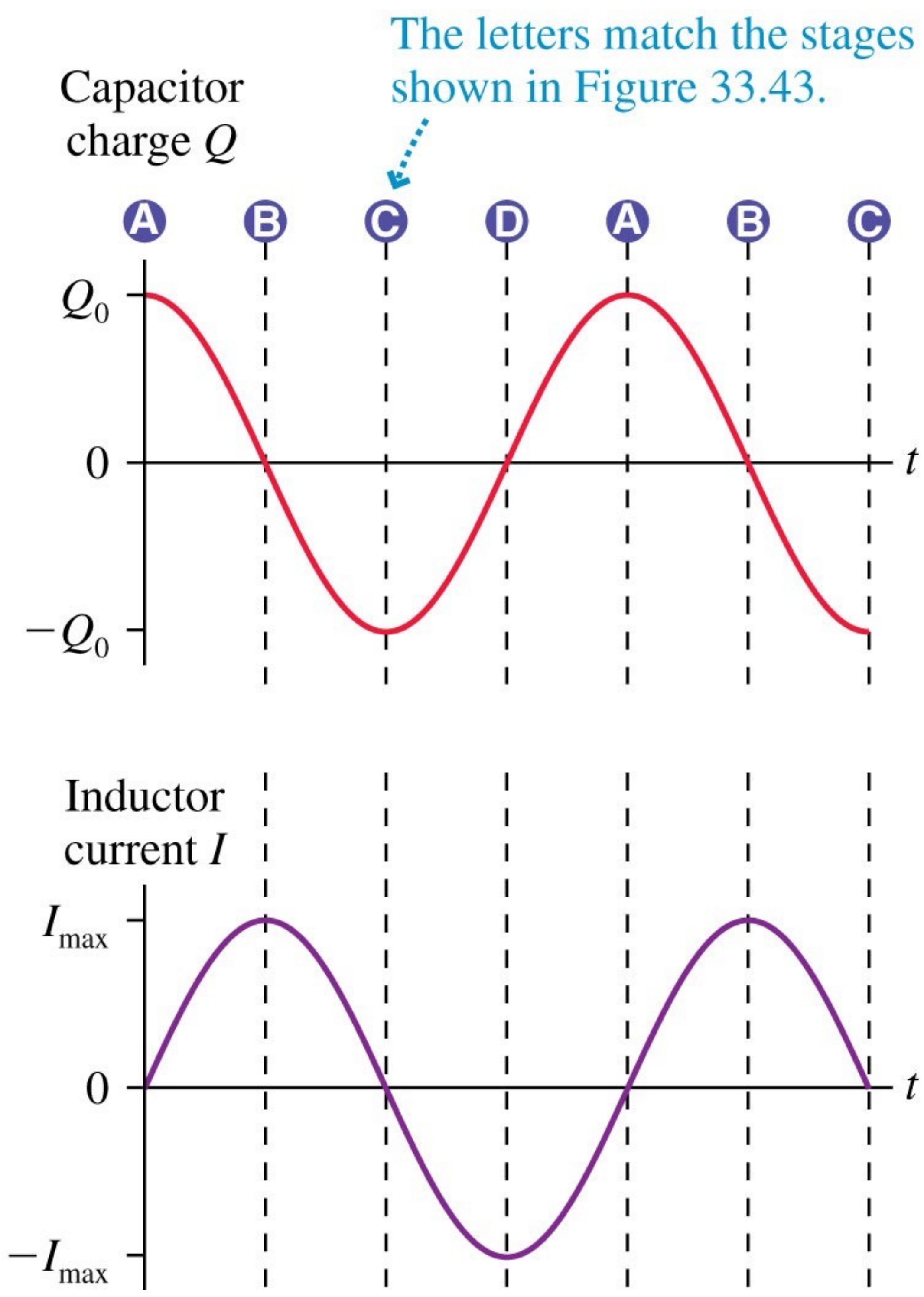
$$\frac{Q}{C} - L\frac{d}{dt}(-\frac{dQ}{dt}) = 0$$

$$\frac{Q}{C} + L\frac{d^2Q}{dt^2} = 0$$

What function satisfies this equation?

Now the math…



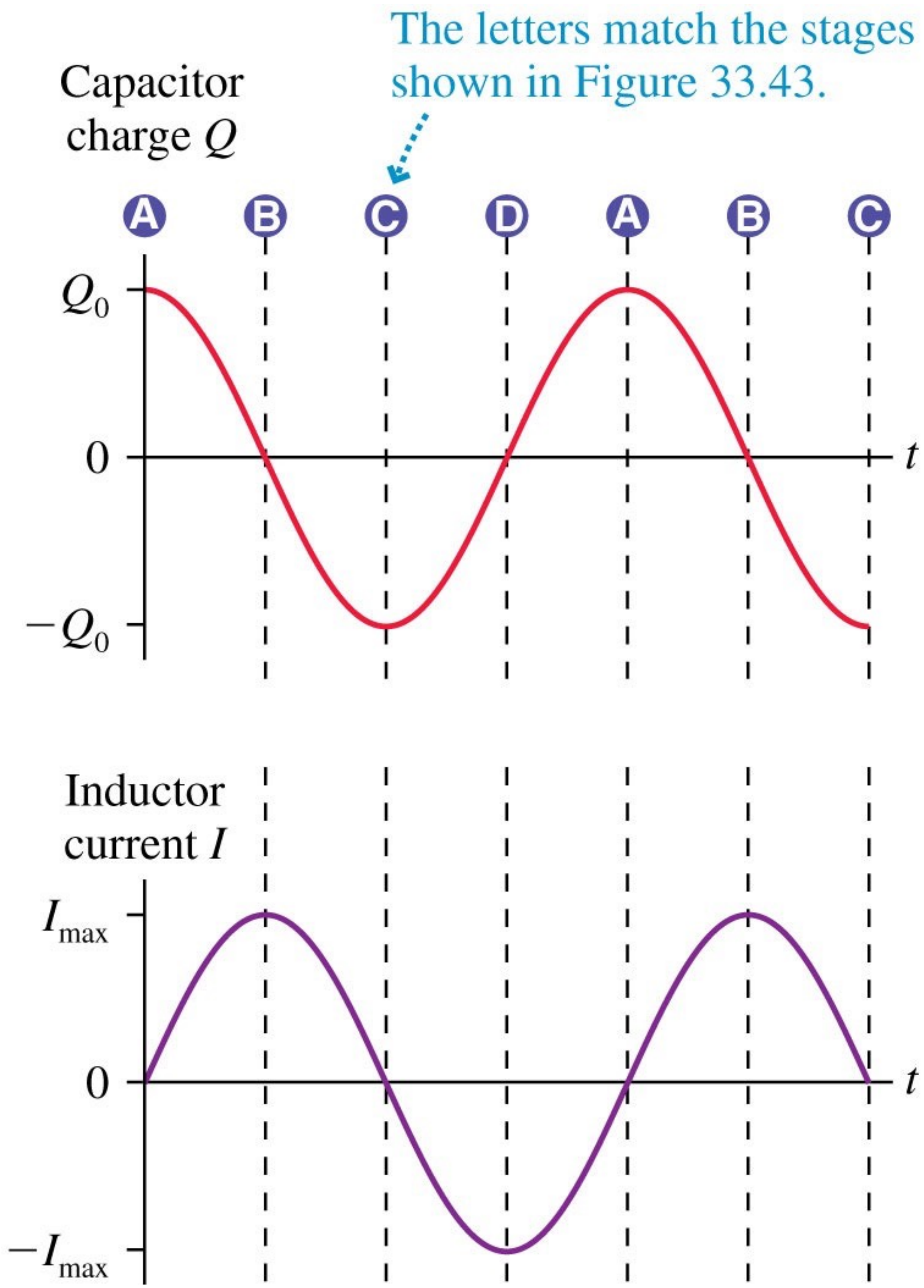
$$= -\frac{dQ}{dt}$$

What function satisfies this equation?

Now the math…

$$Q = Q_0 \cos \omega t$$

$$\omega = \sqrt{\frac{1}{LC}}$$



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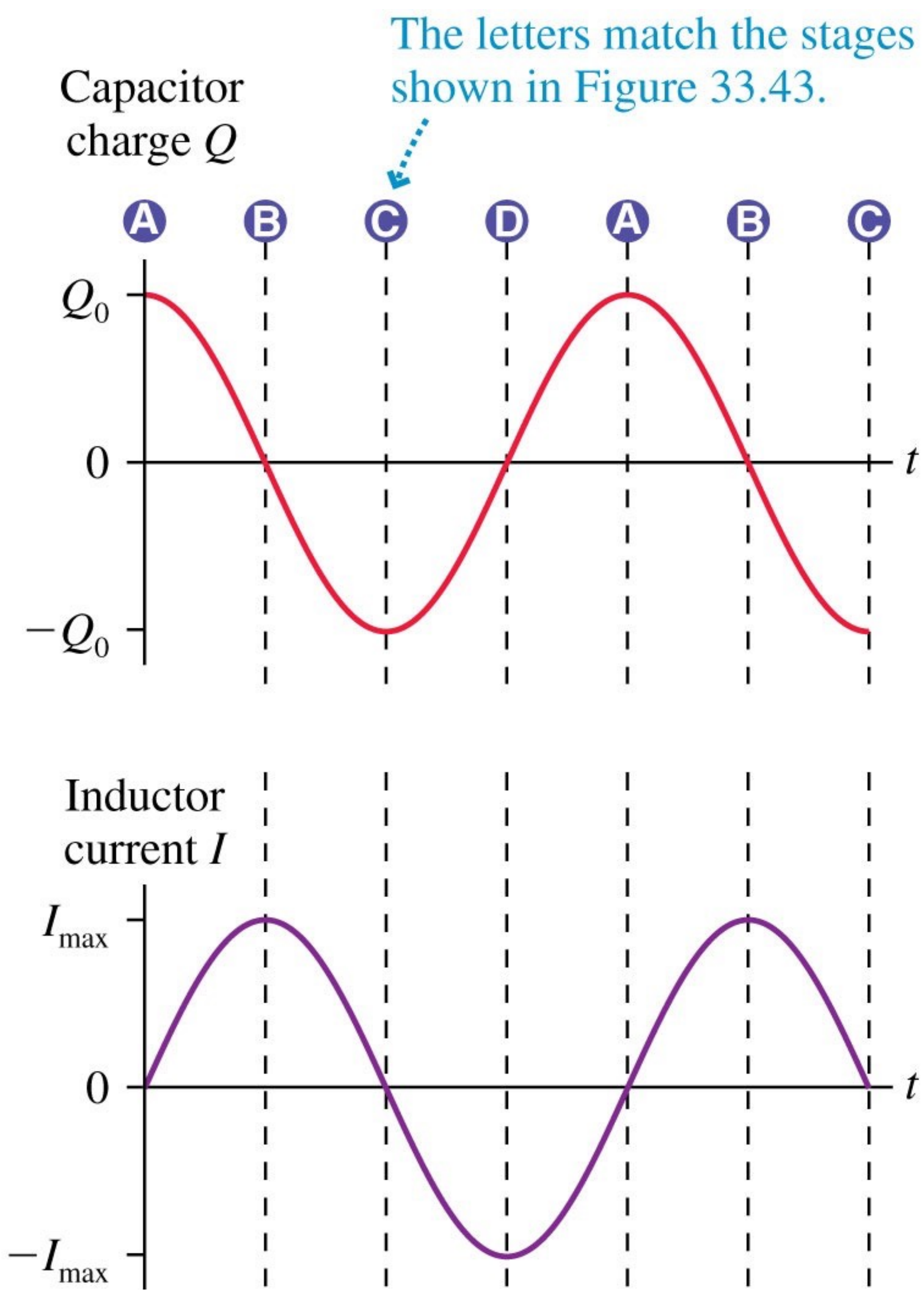


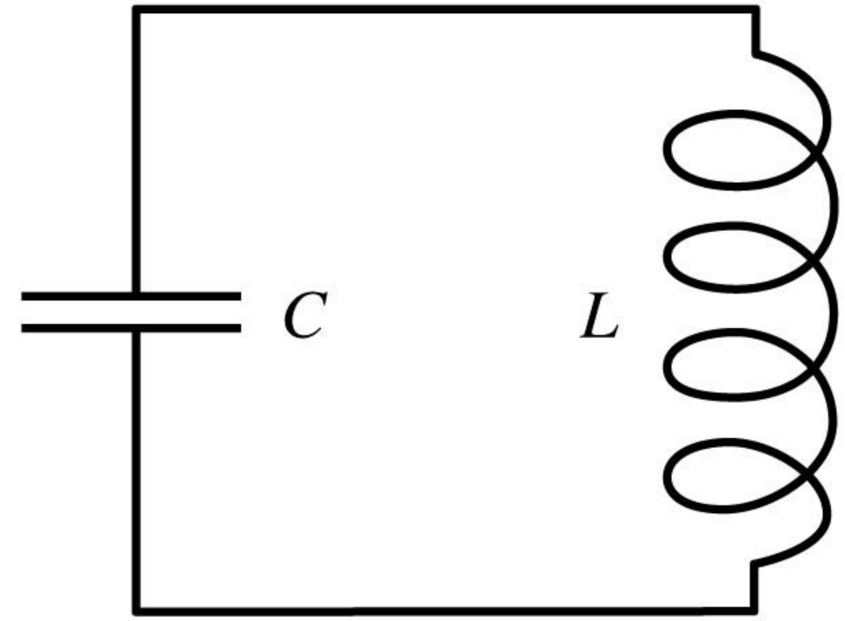
$$= -\frac{dQ}{dt}$$

$$\omega = \sqrt{\frac{1}{LC}}$$

applet

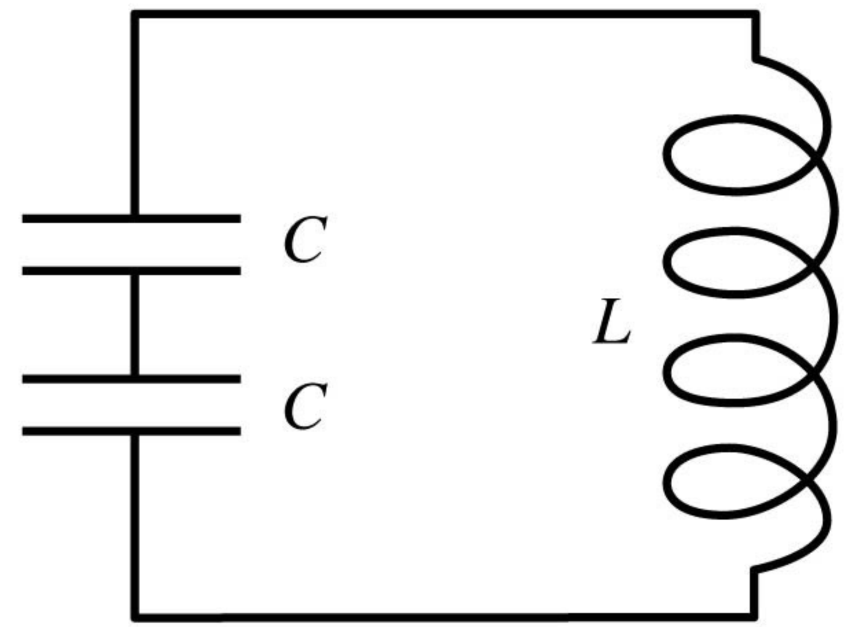
What function satisfies this equation?

Question #10



If the top circuit has an oscillation frequency of 1000 Hz, the frequency of the bottom circuit is

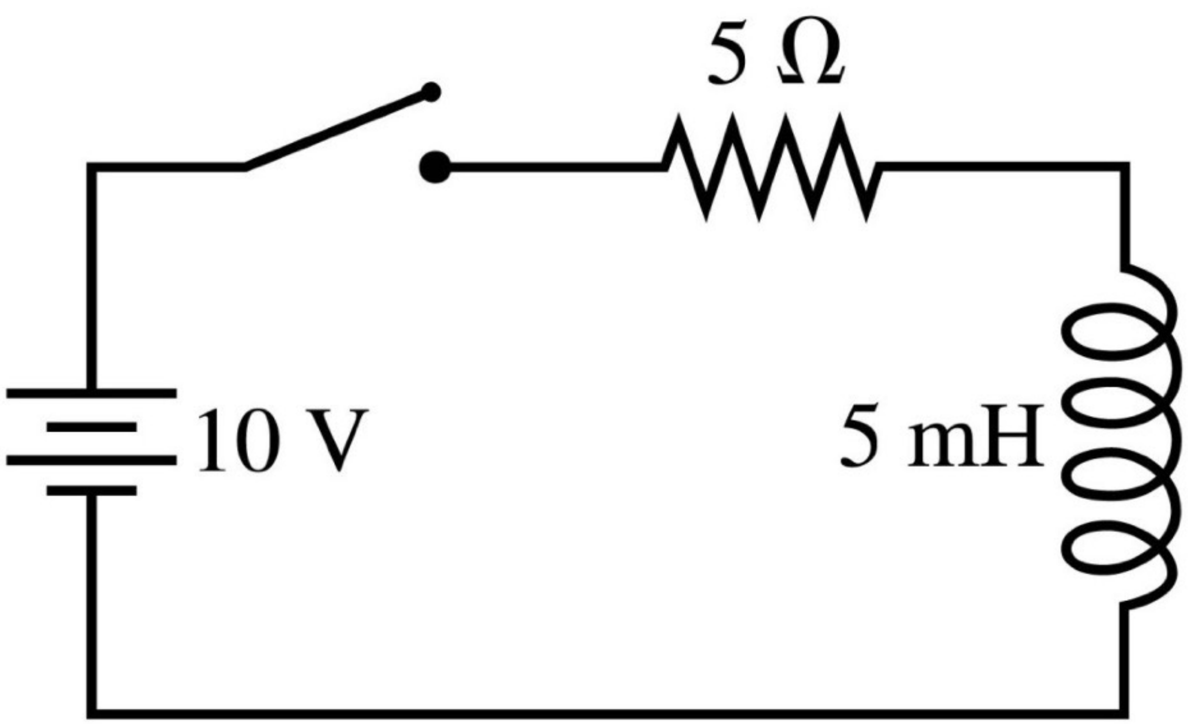
A. 500 Hz.
B. 1410 Hz.
C. 1000 Hz.
D. 2000 Hz.
E. 707 Hz.



Question #11

What is the battery current immediately after the switch has closed?

A. 0 A
B. 1 A
C. 2 A
D. Undefined



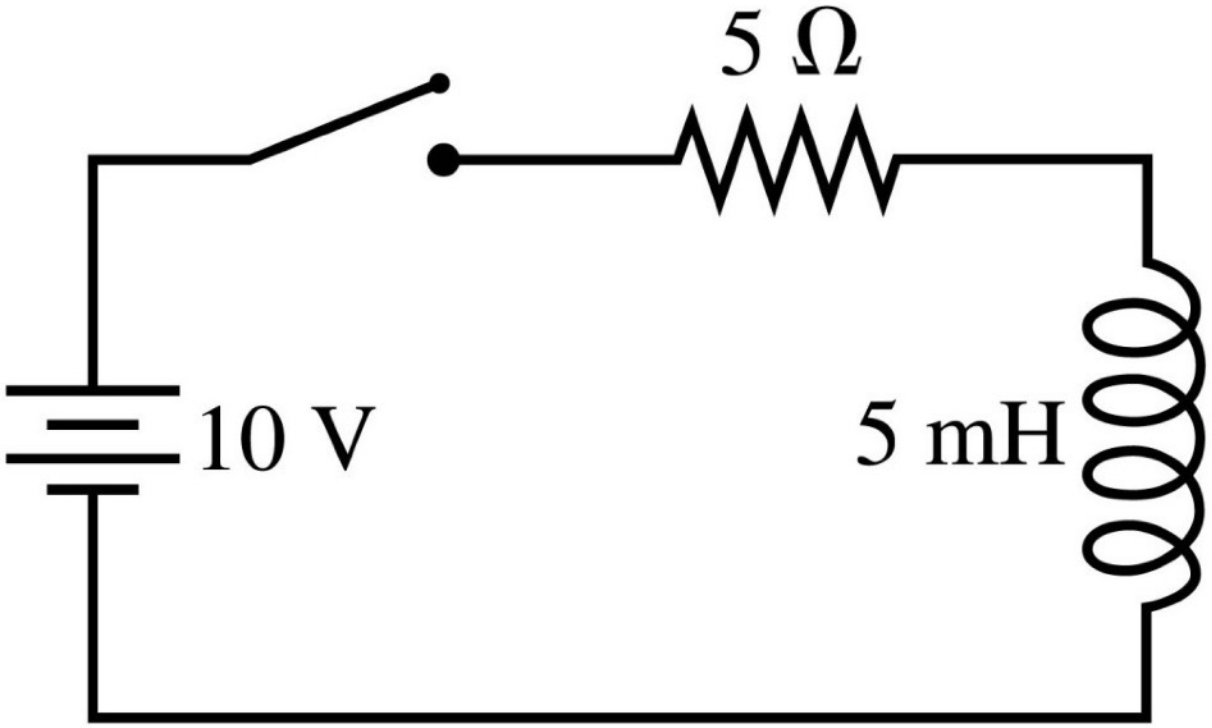
Question #12

What is the battery current after the switch has been closed for a very long time?

B. 0 A

C. 1 A

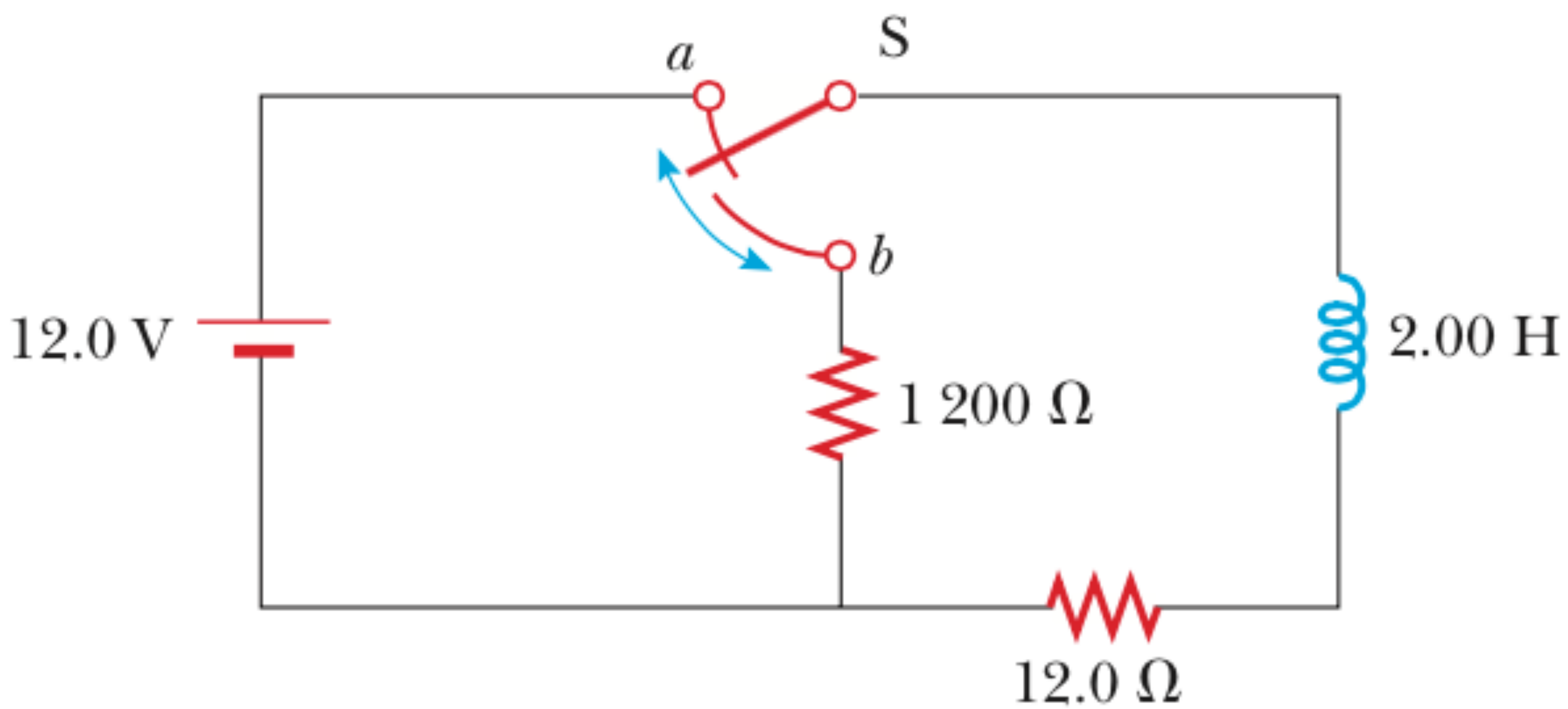
D. 2 A



L-R Circuits

Describe what will happen when the switch is placed in position a.

Describe what will happen when the switch is moved from a to b.



Now the math…

$$\Delta V_R + \Delta V_L = 0$$

Now the math…

$$\Delta V_R + \Delta V_L = 0$$

$$-IR - L\frac{dI}{dt} = 0$$

Now the math…

$$\Delta V_R + \Delta V_L = 0$$

$$-IR - L\frac{dI}{dt} = 0$$

$$-IR = L\frac{dI}{dt}$$

Now the math…

$$\Delta V_R + \Delta V_L = 0$$

$$-IR - L\frac{dI}{dt} = 0$$

$$-IR = L\frac{dI}{dt}$$

What function satisfies this equation?

Now the math…

$$\Delta V_R + \Delta V_L = 0$$

$$-IR - L\frac{dI}{dt} = 0$$

$$-IR = L\frac{dI}{dt}$$

$$-\frac{R}{L}dt = \frac{dI}{I}$$

What function satisfies this equation?

Now the math…

$$\Delta V_R + \Delta V_L = 0$$

$$-IR - L\frac{dI}{dt} = 0$$

$$I = I_0 e^{-tR/L}$$

$$-IR = L\frac{dI}{dt}$$

$$\tau = \frac{L}{R}$$

$$-\frac{R}{L}dt = \frac{dI}{I}$$

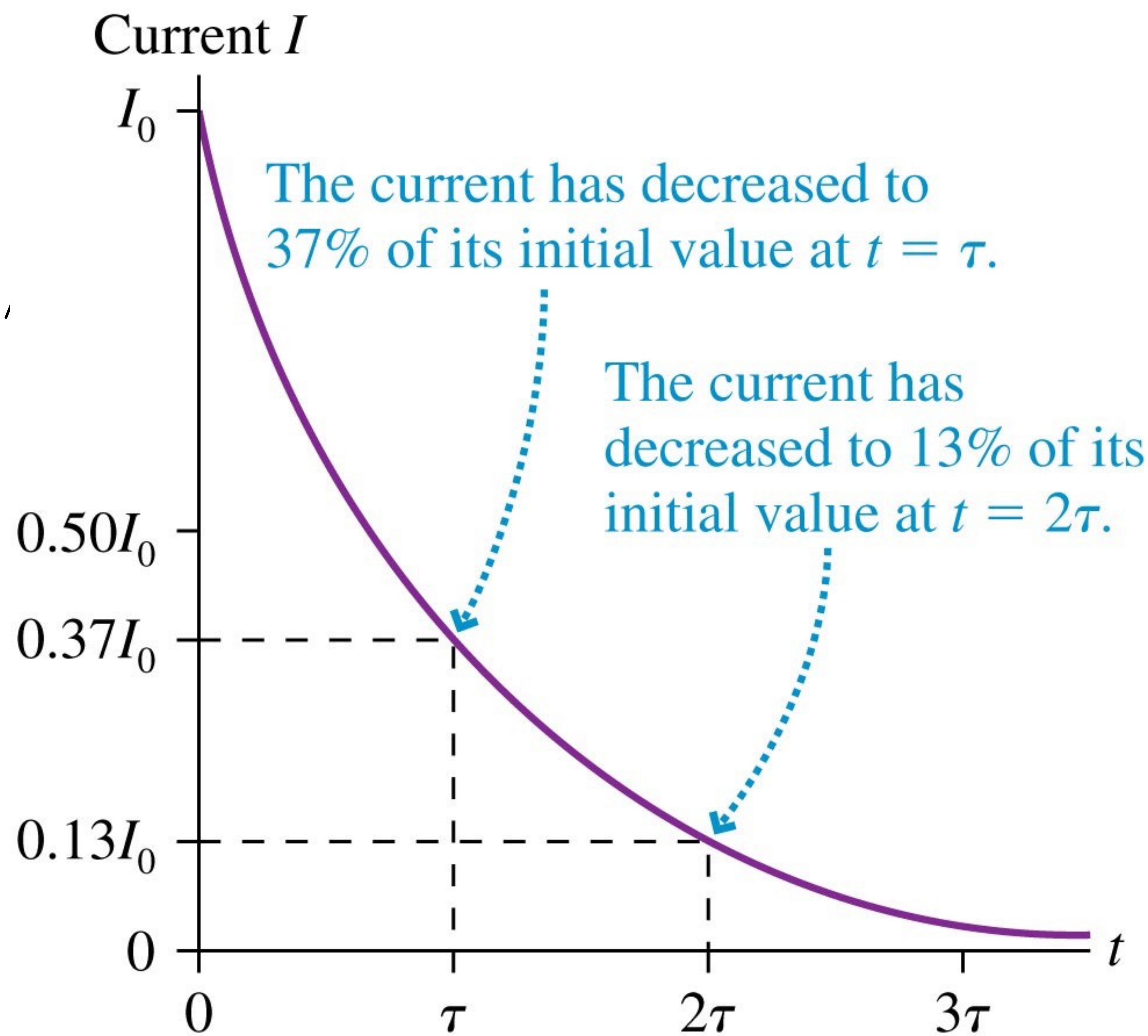
What function satisfies this equation?

Now the math…

$$\Delta V_R + \Delta V_L = 0$$

$$I = I_0 e^{-tR/}$$

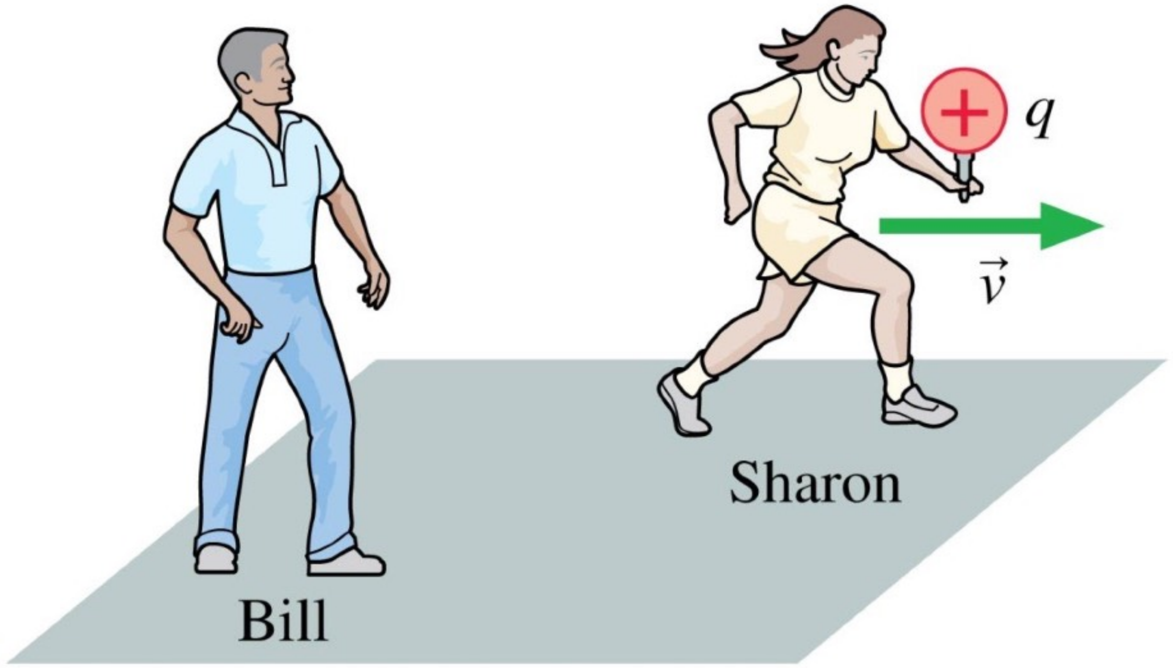
$$\tau = \frac{L}{R}$$



What function satisfies this equation?

Question #13

Sharon runs past Bill while holding a positive charge q. In Bill's reference frame, there is (or are)



A. Only an electric field.

B. An electric and a magnetic field.

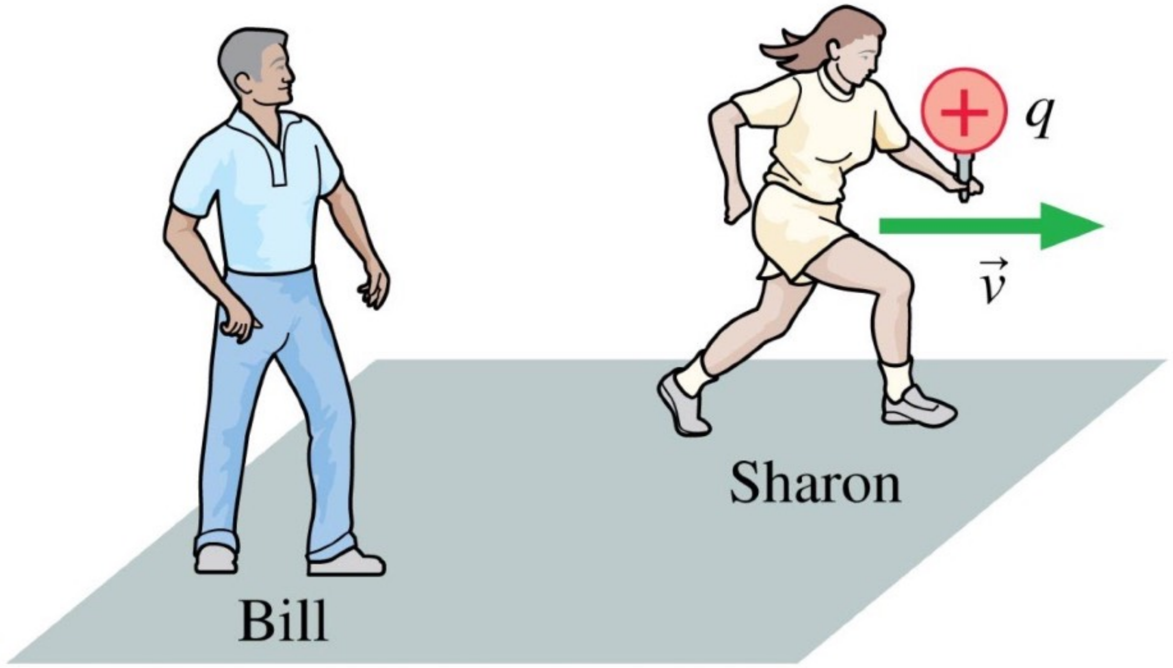
C. Only a magnetic field.

D. No fields.

Question #14

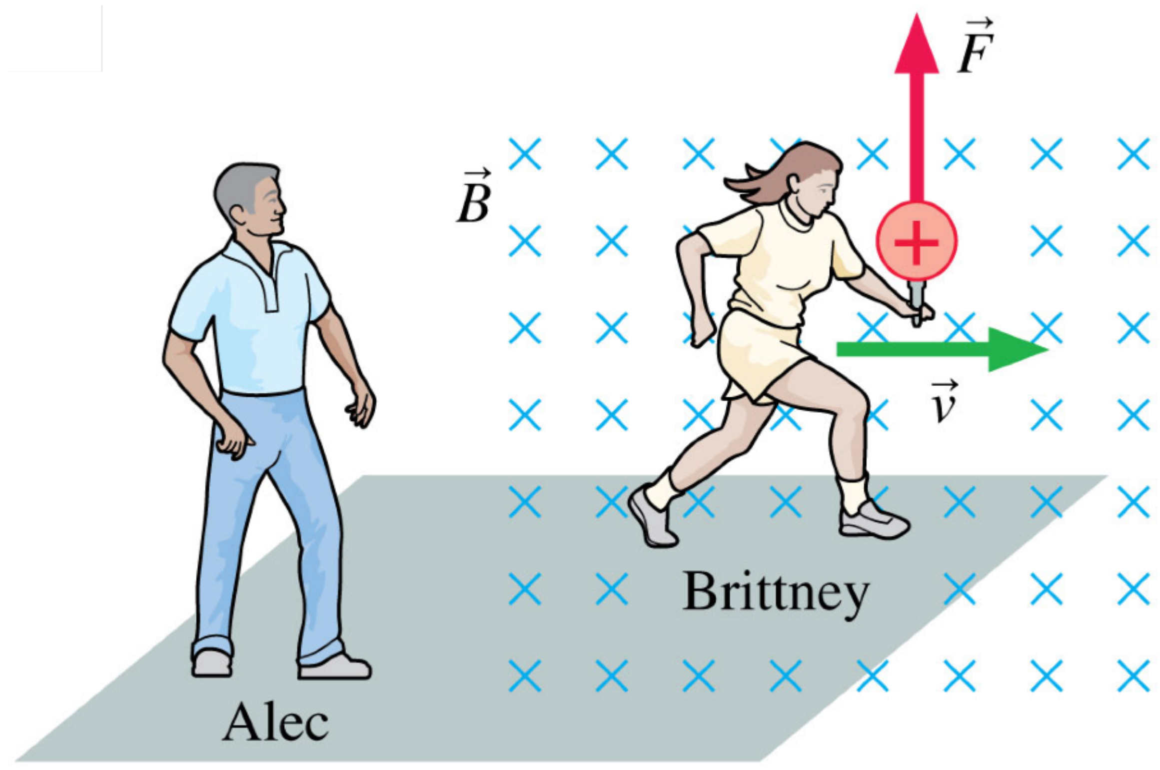
Sharon runs past Bill while holding a positive charge *q*. In Sharon's reference frame, there is (or are)

A. An electric and a magnetic field.
B. Only an electric field.
C. Only a magnetic field.
D. No fields.



Question #15

Brittney runs past Bill while holding a positive charge q. There is a magnetic field pointing into the screen. Does Bill observe a force on the charge?

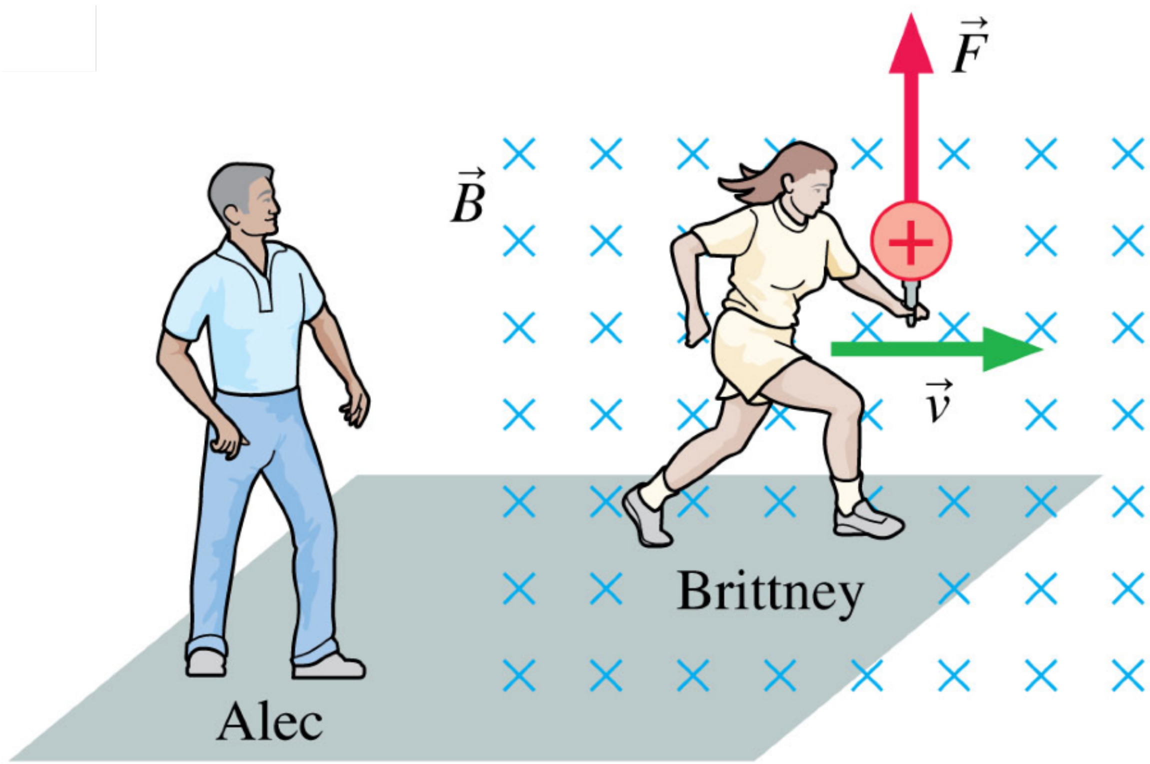


A- Yes

B- No

Question #16

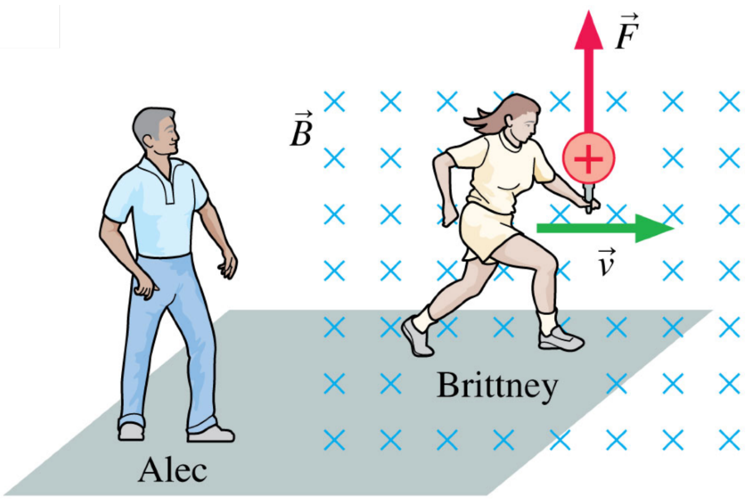
Brittney runs past Bill while holding a positive charge q. There is a magnetic field pointing into the screen. Does **Brittney** observe a force on the charge?

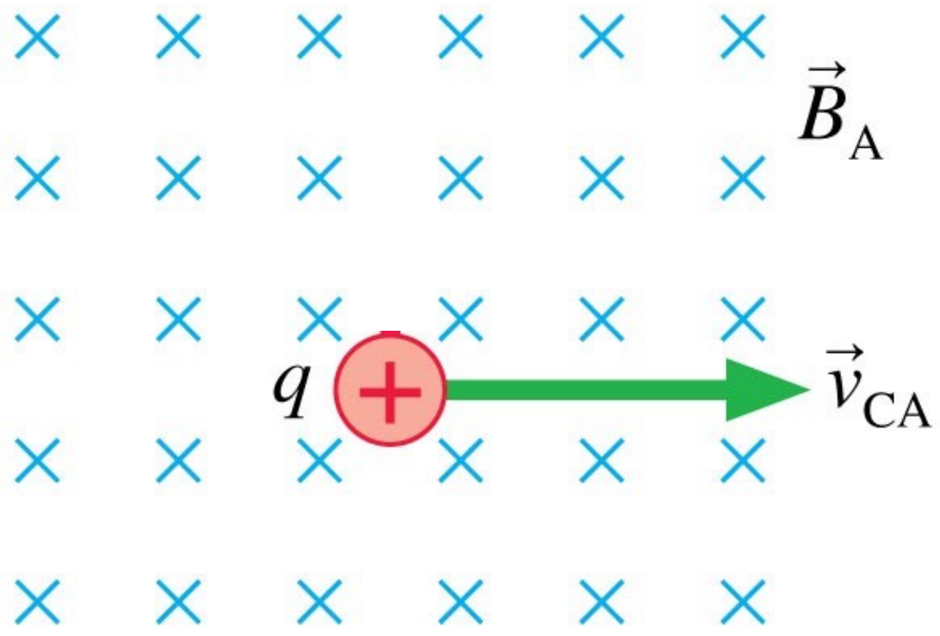


A- Yes

B- No

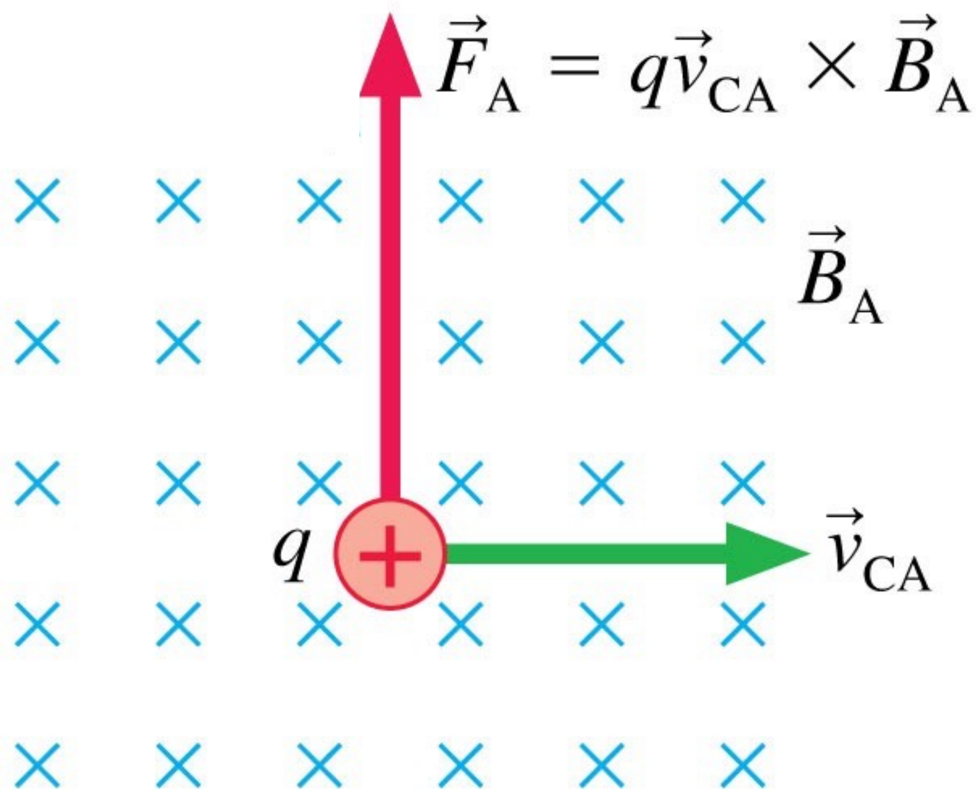
Situation in Alec's reference frame

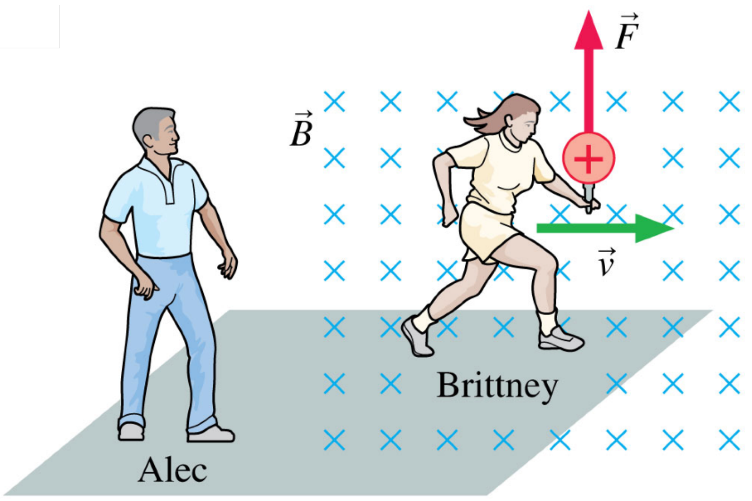




What force does Alec observe that the charge experiences?

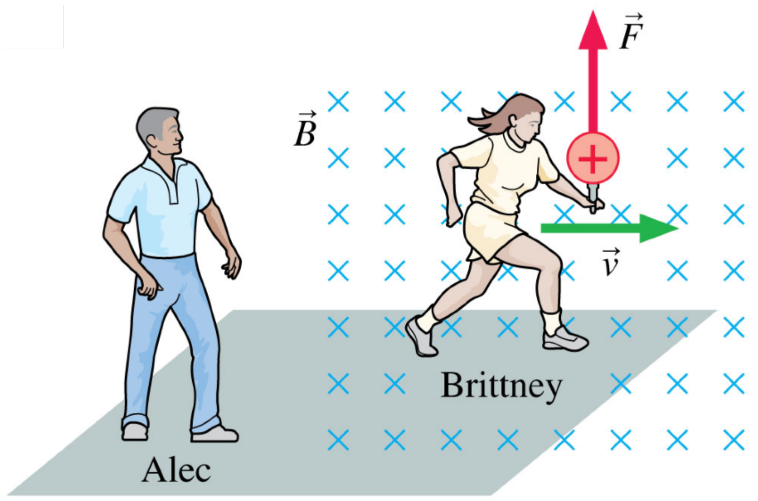
Situation in Alec's reference frame

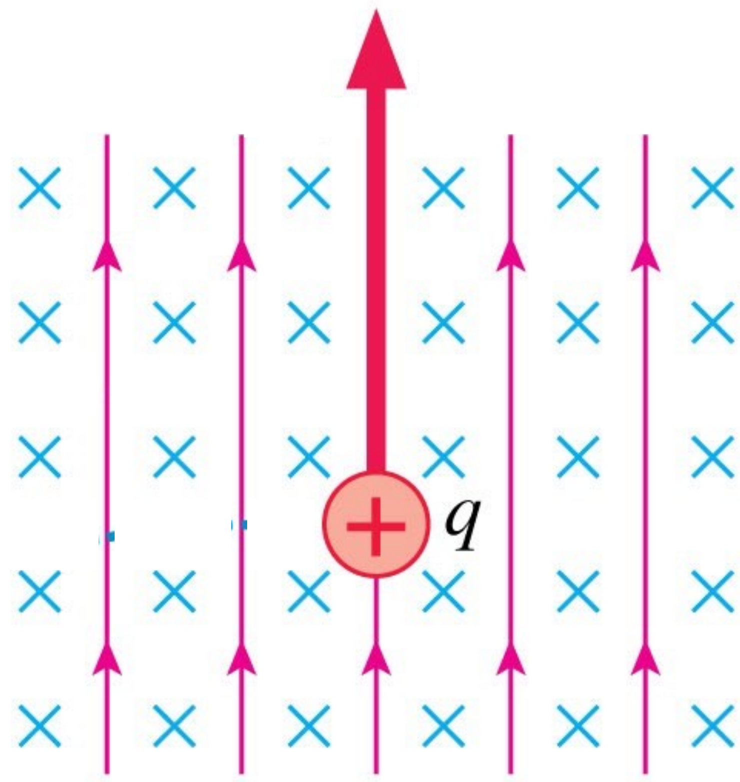




What force does Alec observe that the charge experiences?

Situation in Brittney's reference frame



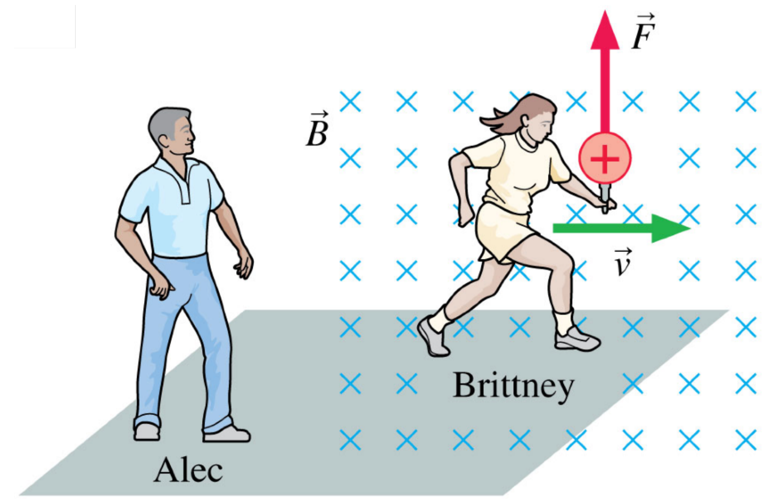


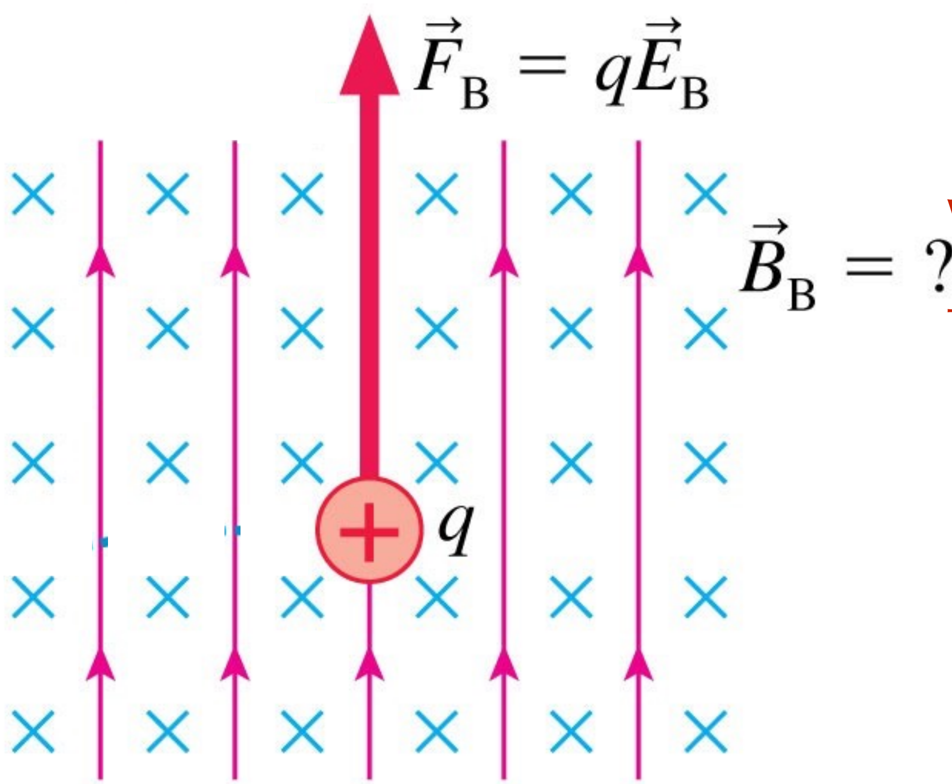
What kind of a force could cause this?

$$\vec{F} = q\vec{E}$$

$$\vec{E}_B = \vec{v}_{BA} \times \vec{B}_A$$

Situation in Brittney's reference frame





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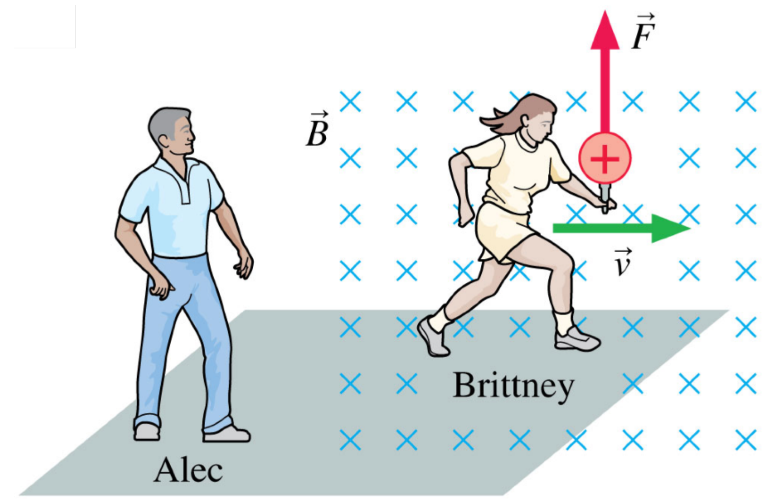
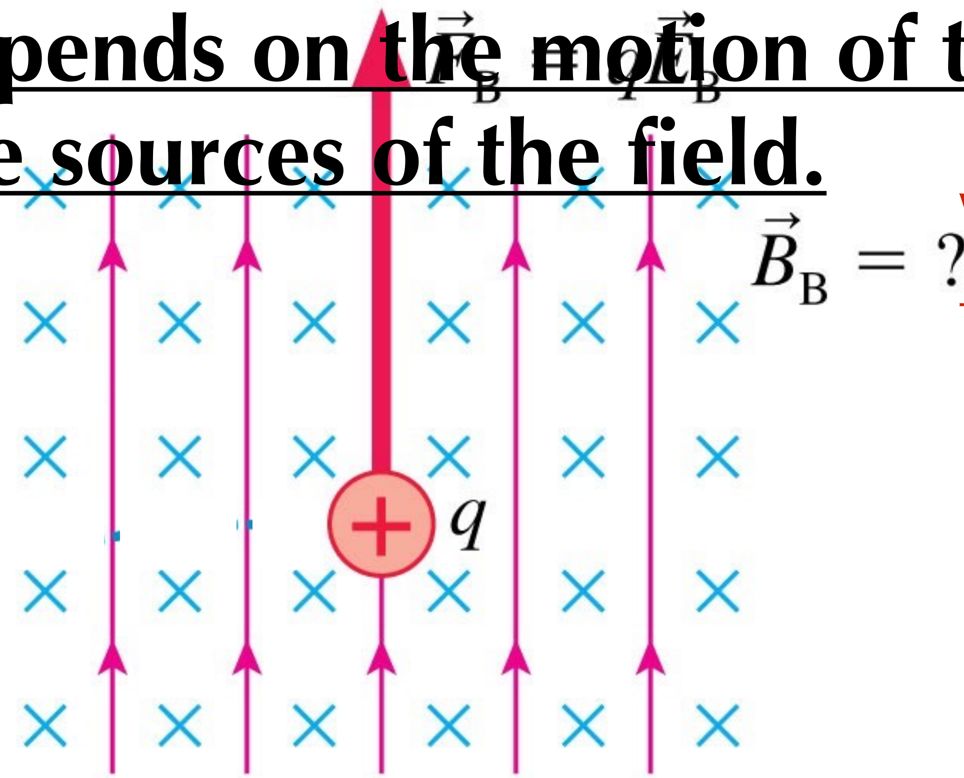
Situation in Brittney's reference frame



- **Whether a field is seen as "electric" or "magnetic" depends on the motion of the reference frame relative to the sources of the field.**



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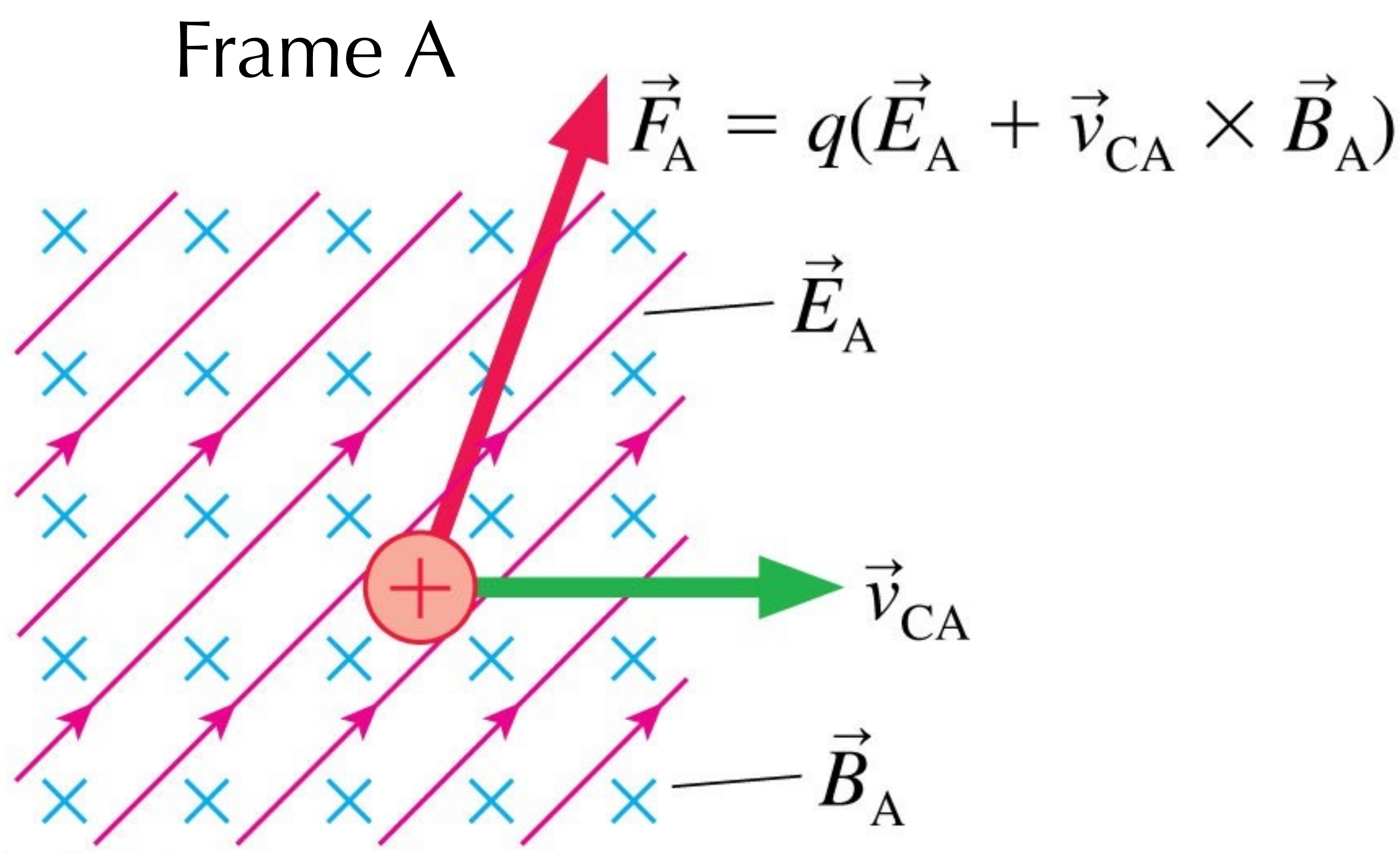
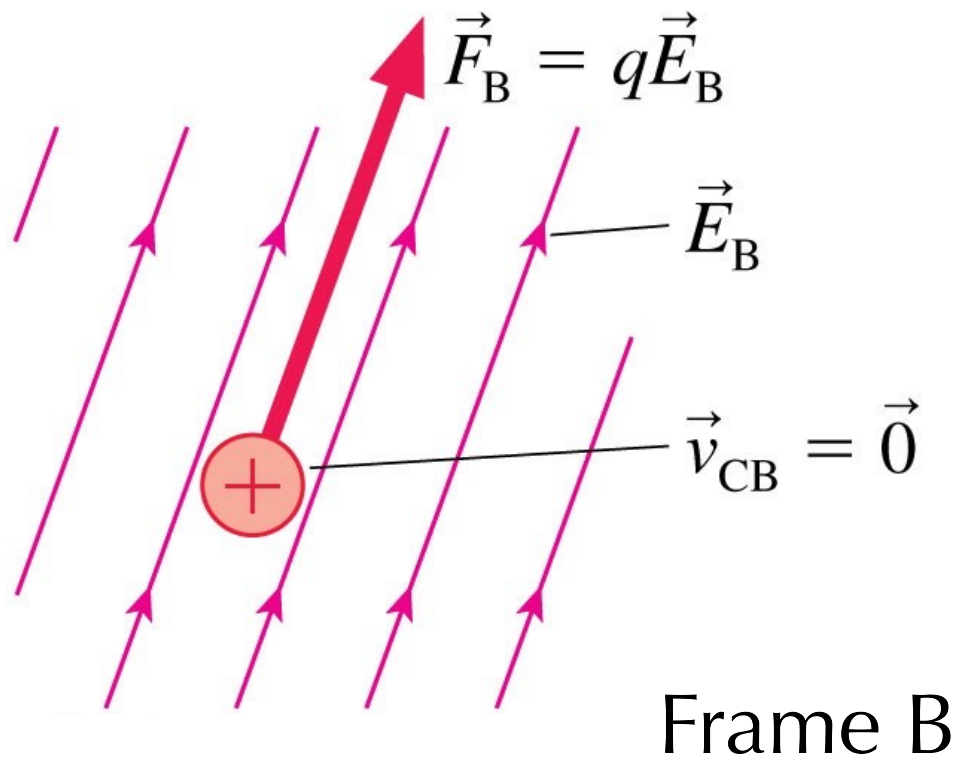
The Transformation equations



$$\vec{F}_A = \vec{F}_B$$



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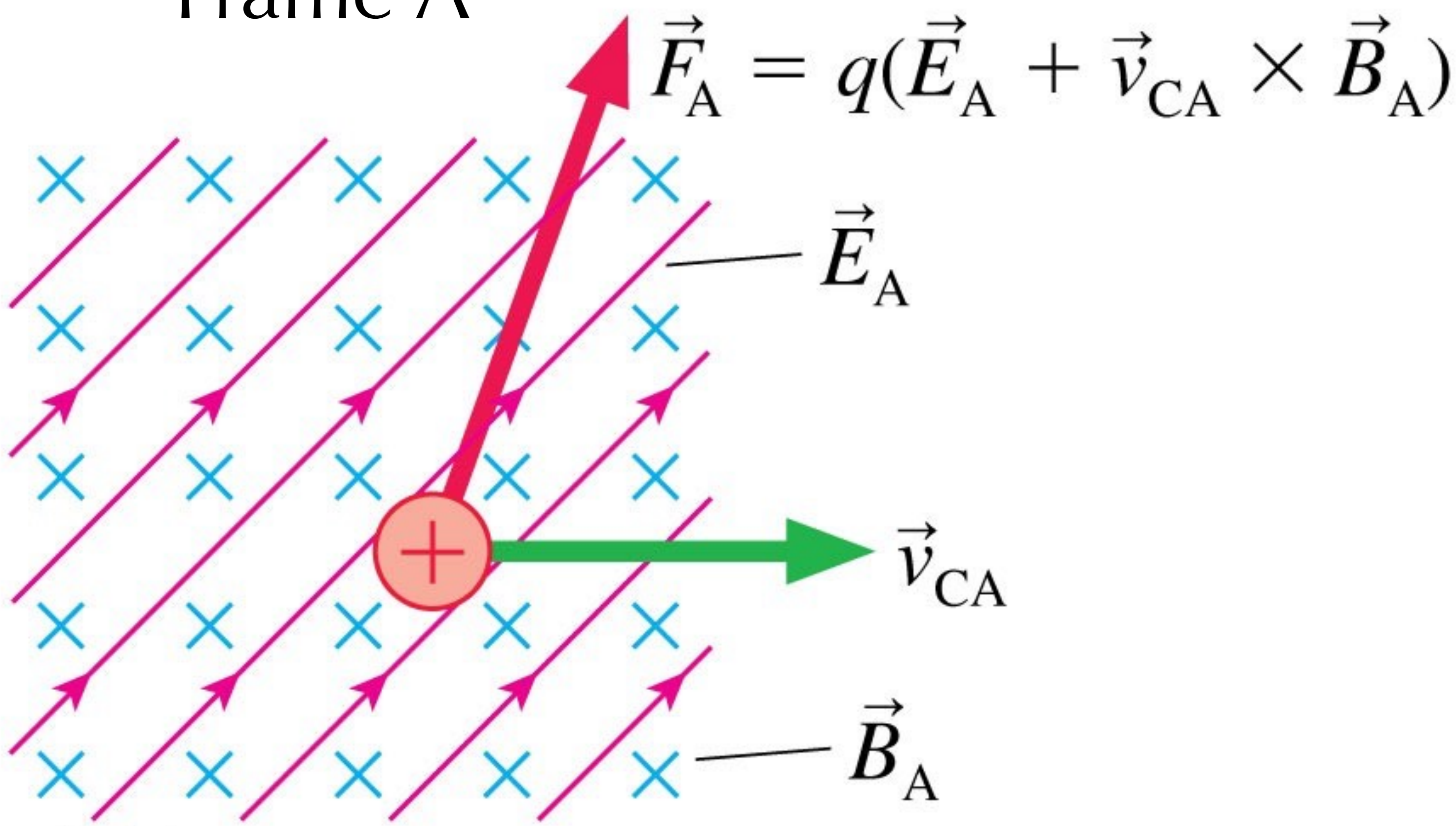
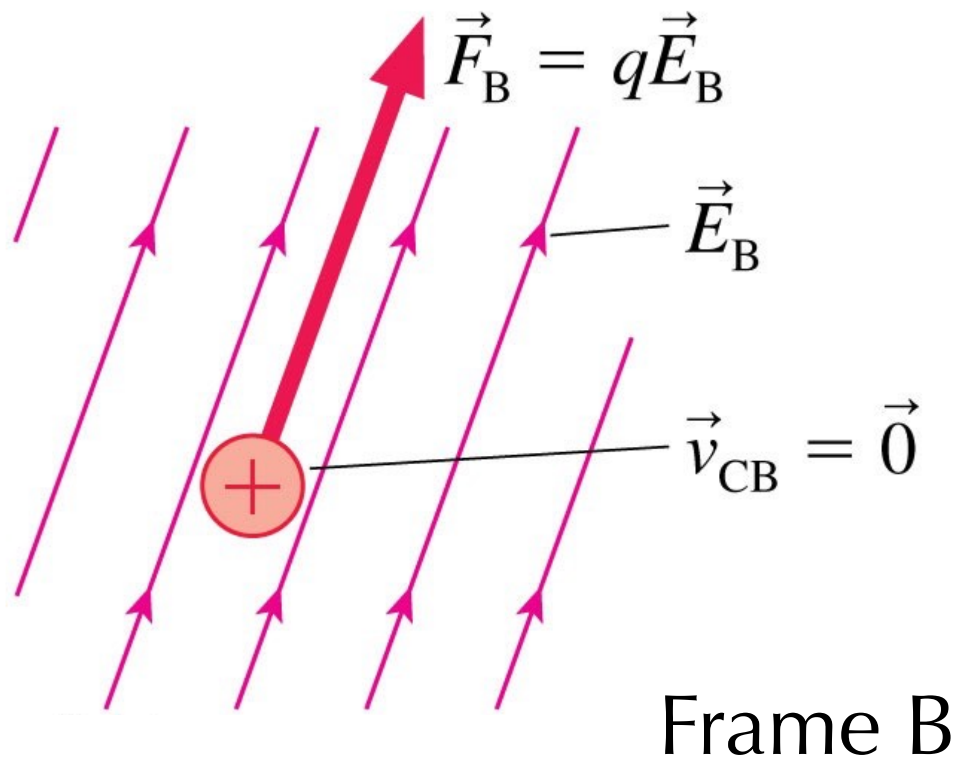


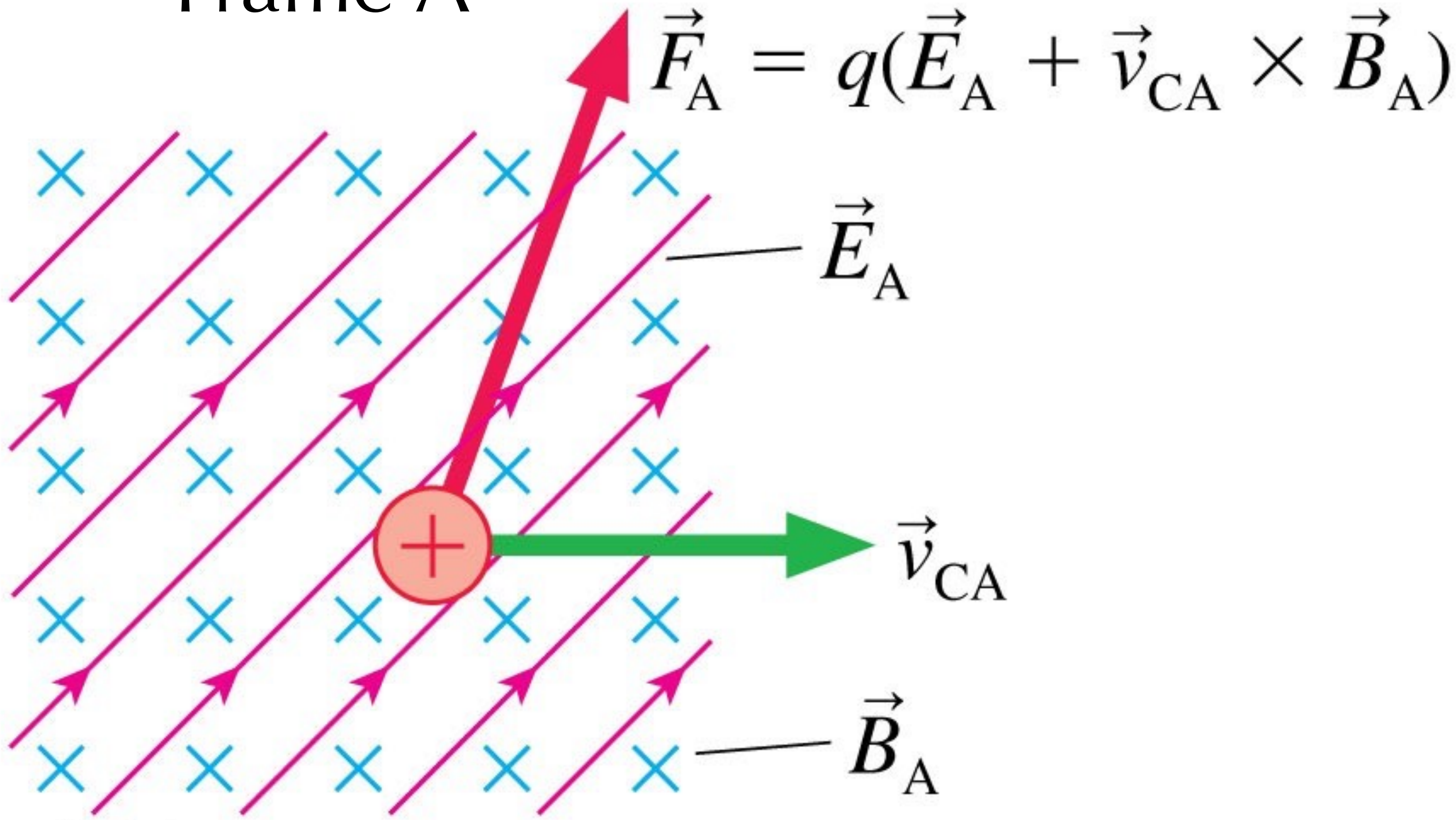
$$\vec{F}_A = \vec{F}_B$$

$$q\vec{E}_B = q(\vec{E}_A + \vec{v}_{BA} \times \vec{B}_A)$$



The Transformation equations

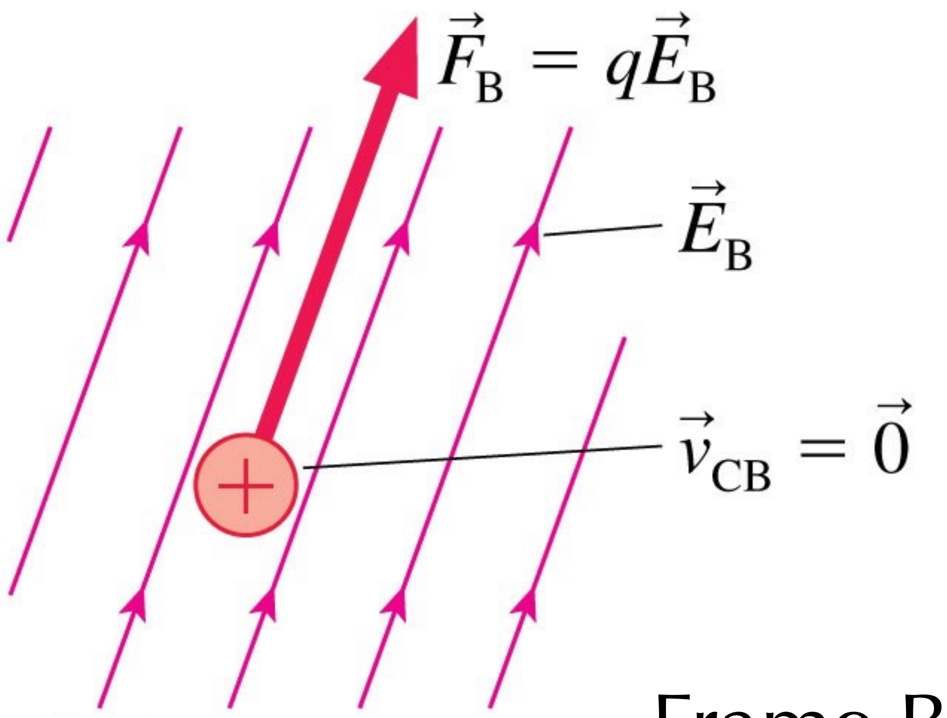
Frame A



$$\vec{F}_A = \vec{F}_B$$

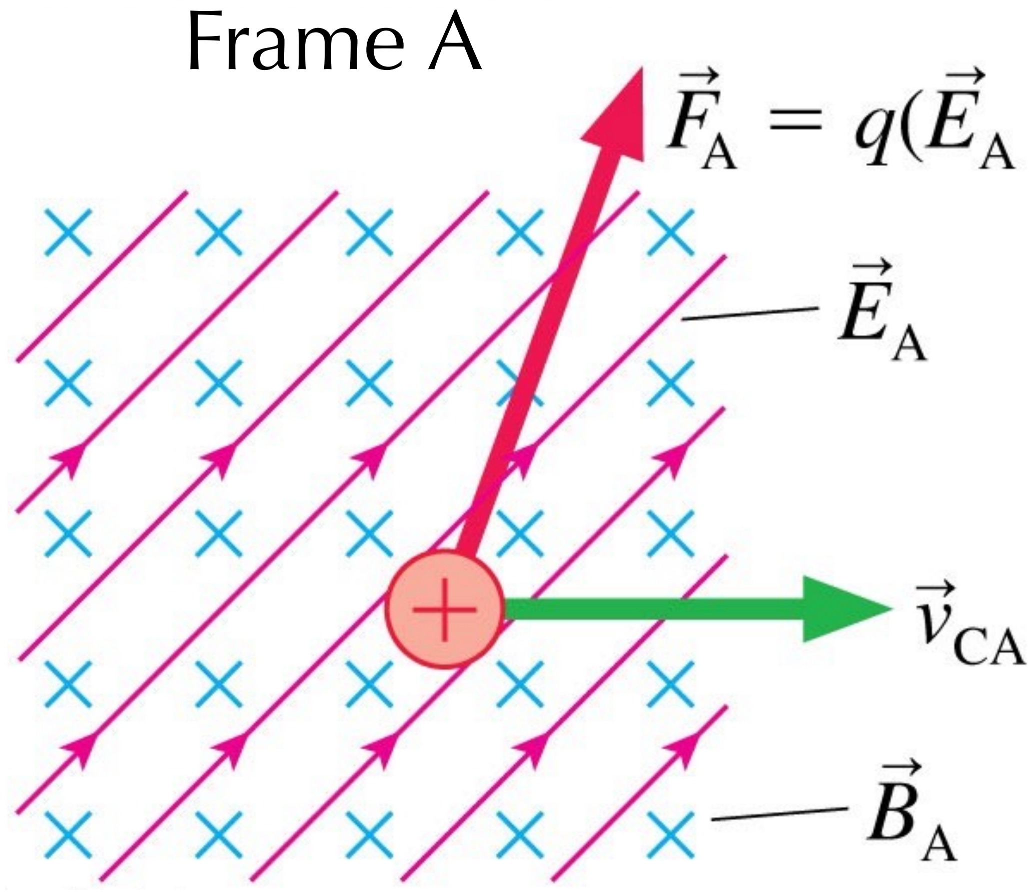
$$q\vec{E}_B = q(\vec{E}_A + \vec{v}_{BA} \times \vec{B}_A)$$

$$\vec{E}_B = \vec{E}_A + \vec{v}_{BA} \times \vec{B}_A$$



Frame B

The Transformation equations

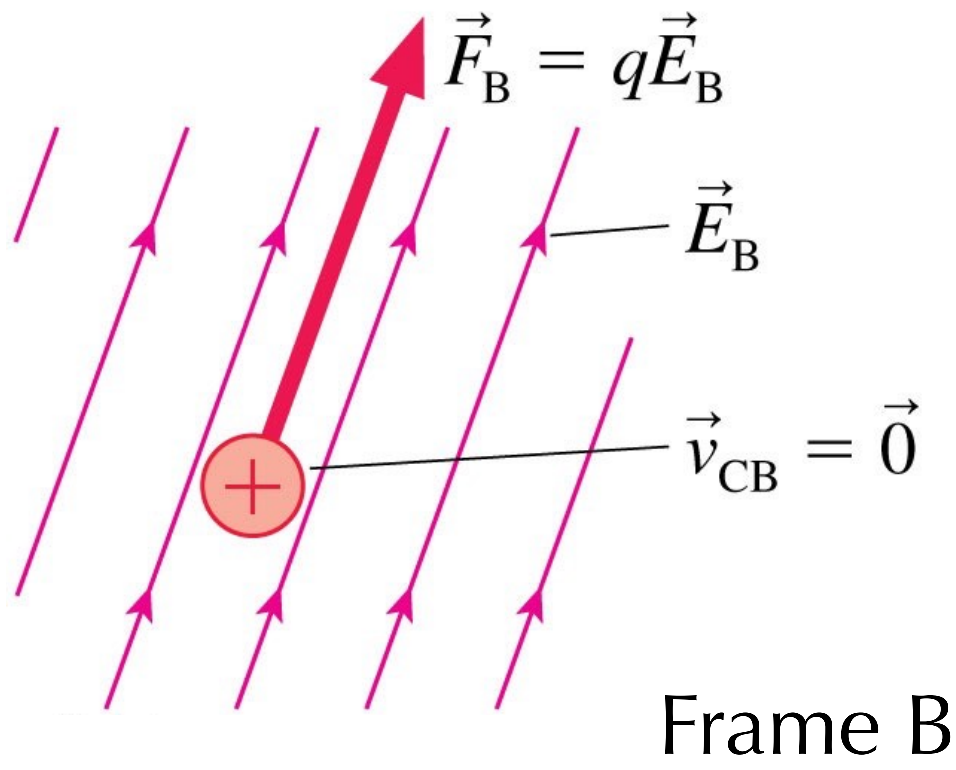


$$\vec{B}_B = \vec{B}_A - \frac{1}{c^2}\vec{v}_{BA} \times \vec{E}_A$$

$$\vec{F}_A = \vec{F}_B$$

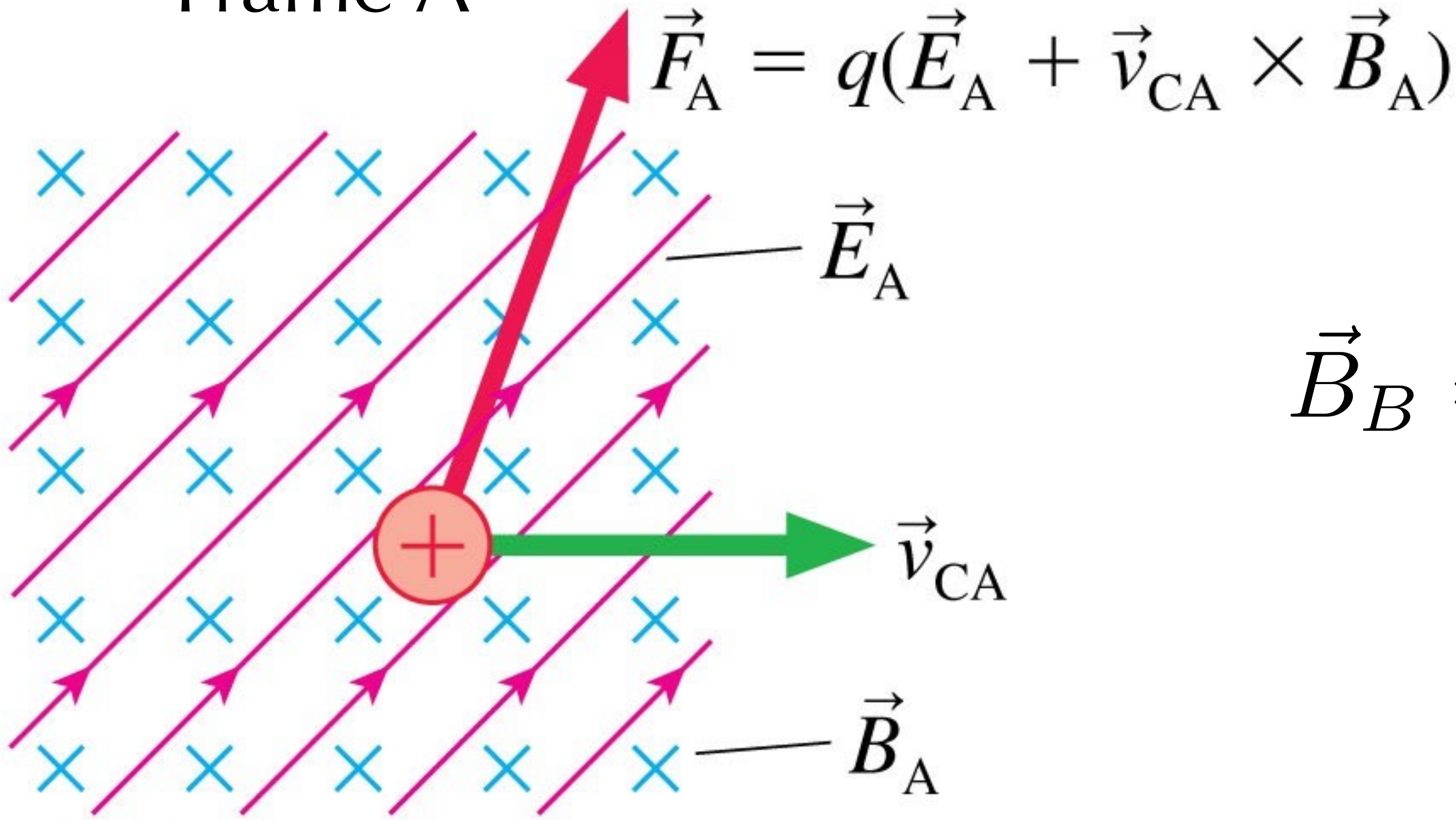
$$q\vec{E}_B = q(\vec{E}_A + \vec{v}_{BA} \times \vec{B}_A)$$

$$\vec{E}_B = \vec{E}_A + \vec{v}_{BA} \times \vec{B}_A$$



The Transformation equations

Frame A



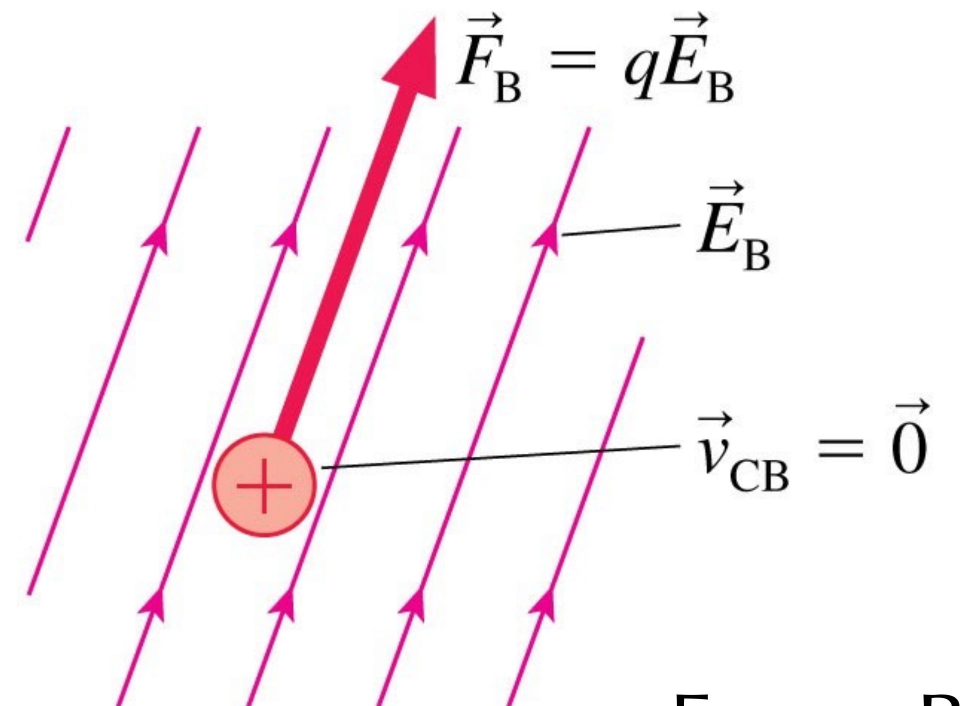
$$v = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$$

$$\vec{B}_B = \vec{B}_A - \frac{1}{c^2}\vec{v}_{BA} \times \vec{E}_A$$

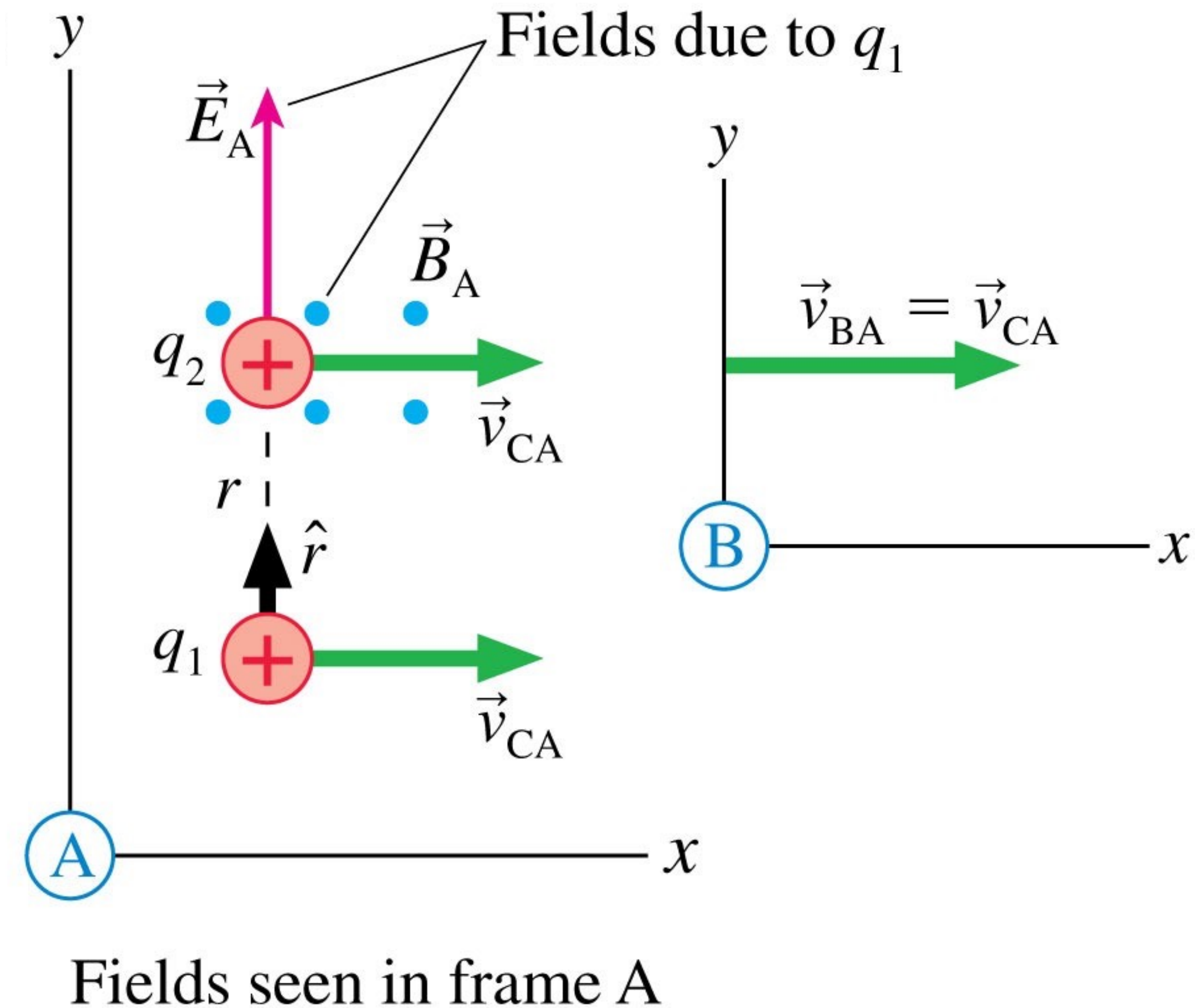
$$\vec{F}_A = \vec{F}_B$$

$$q\vec{E}_B = q(\vec{E}_A + \vec{v}_{BA} \times \vec{B}_A)$$

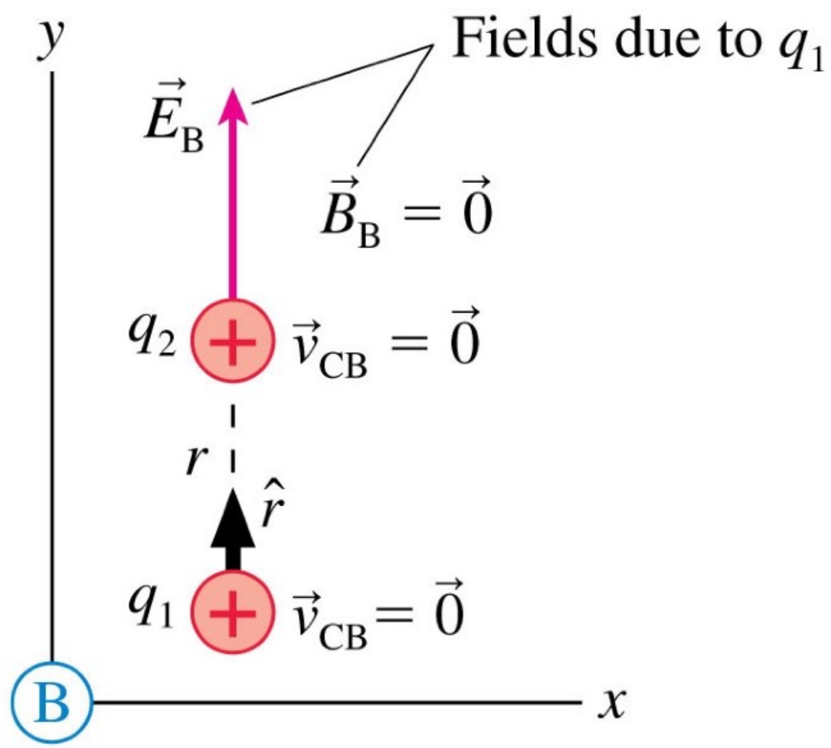
$$\vec{E}_B = \vec{E}_A + \vec{v}_{BA} \times \vec{B}_A$$



Frame B



What fields does this observer see?



Fields seen in frame B

What fields does this observer see?

$$\vec{B}_B = \vec{B}_A - \frac{1}{c^2}\vec{v}_{BA} \times \vec{E}_A$$

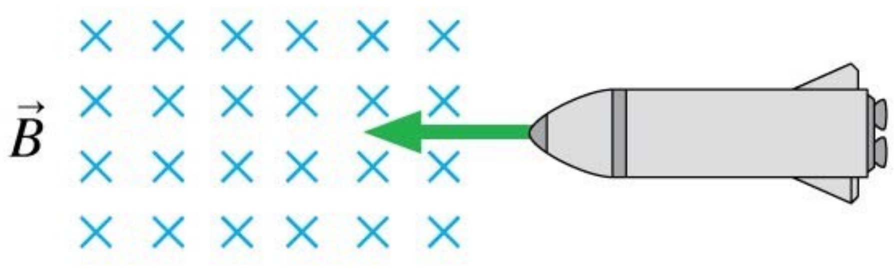
$$\vec{E}_B = \vec{E}_A + \vec{v}_{BA} \times \vec{B}_A$$

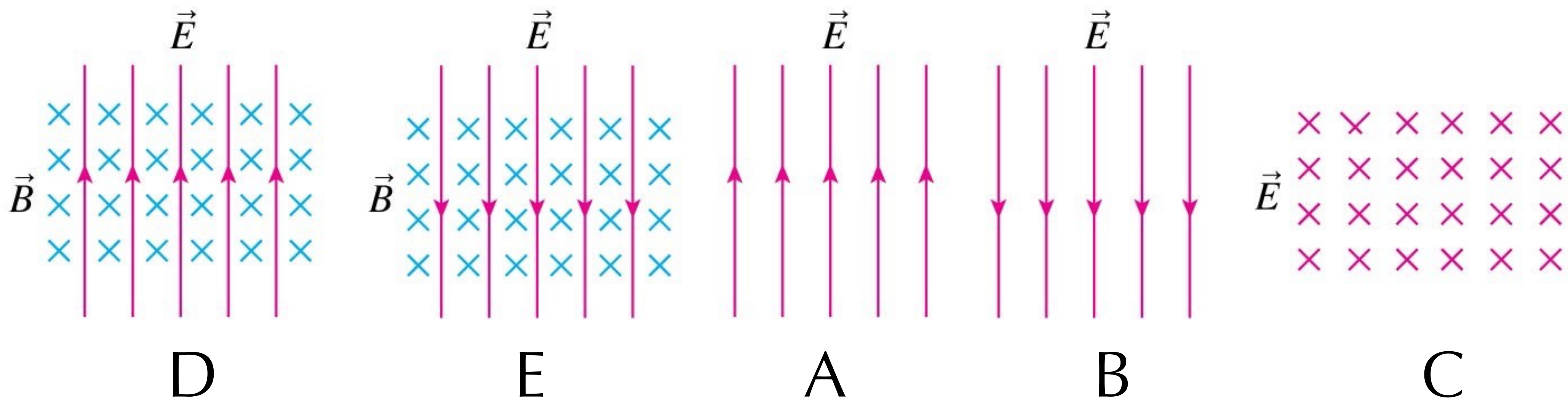
Question #17

$$\vec{B}_B = \vec{B}_A - \frac{1}{c^2}\vec{v}_{BA} \times \vec{E}_A$$

$$\vec{E}_B = \vec{E}_A + \vec{v}_{BA} \times \vec{B}_A$$

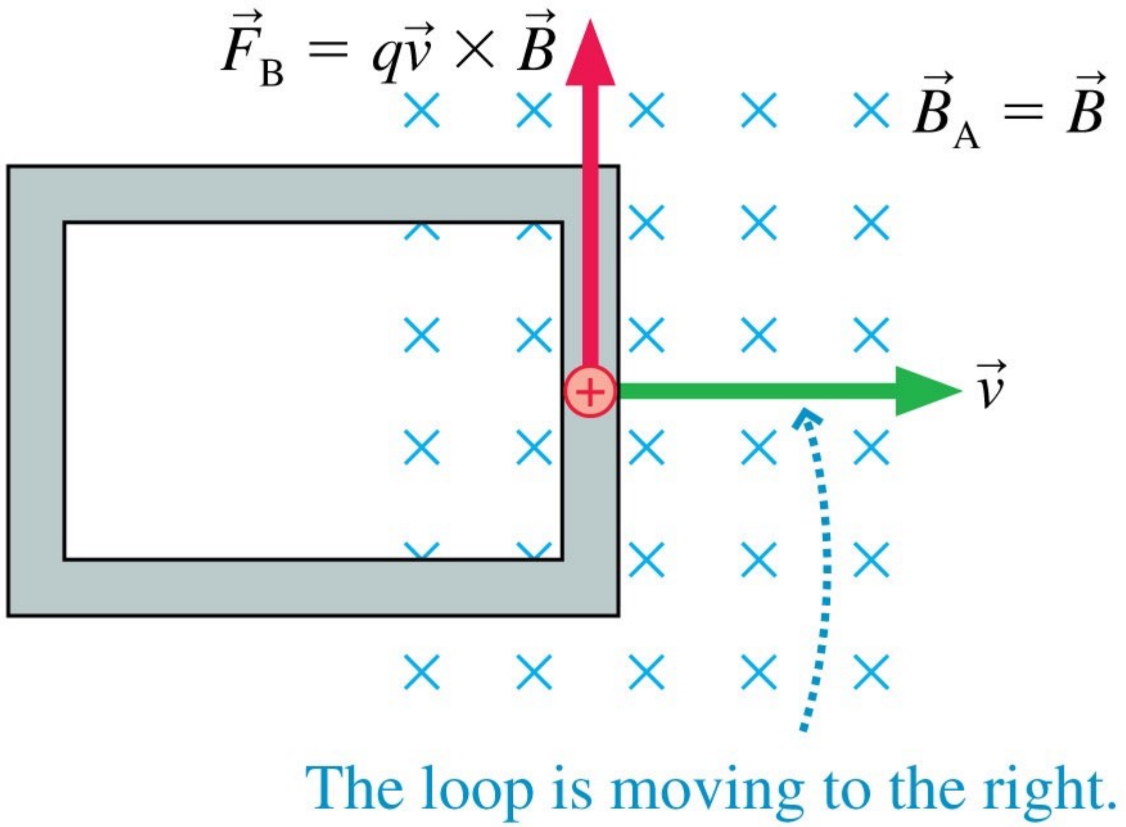
Experimenters on earth have created the magnetic field shown. A rocket flies through the field, from right to left. Which are the field (or fields) in the rocket's reference frame?





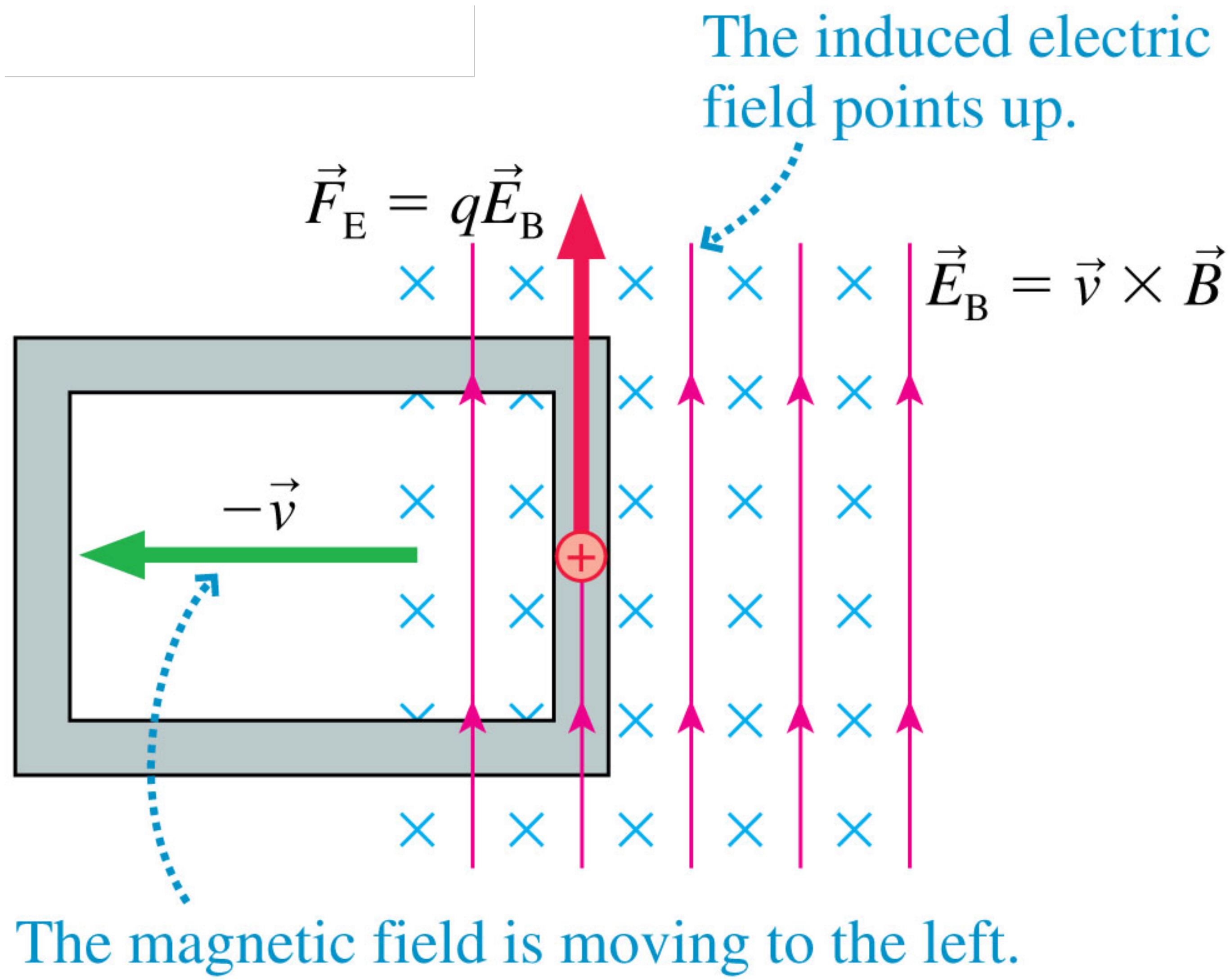
Faraday's Law again

Frame where loop is moving!



Faraday's Law again

Frame where loop is stationary!

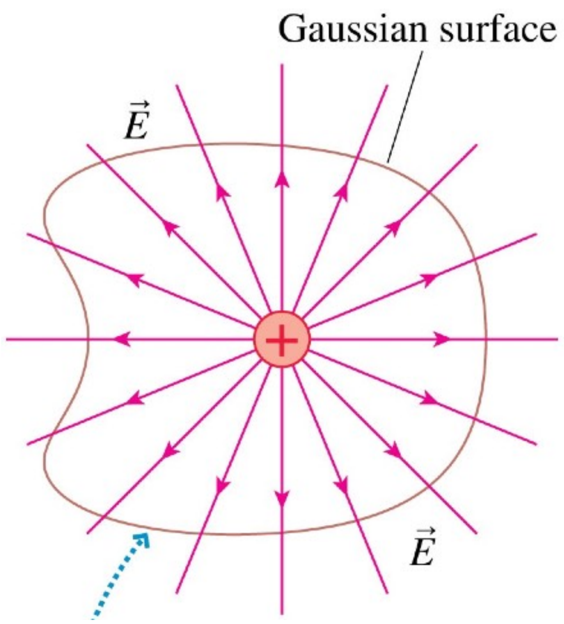


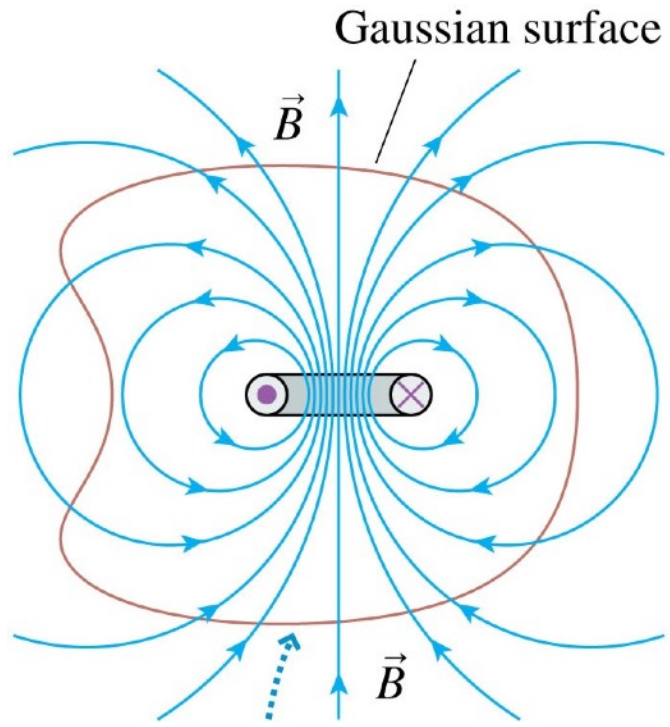
How do these transformation equations explain the situation in this frame of reference?

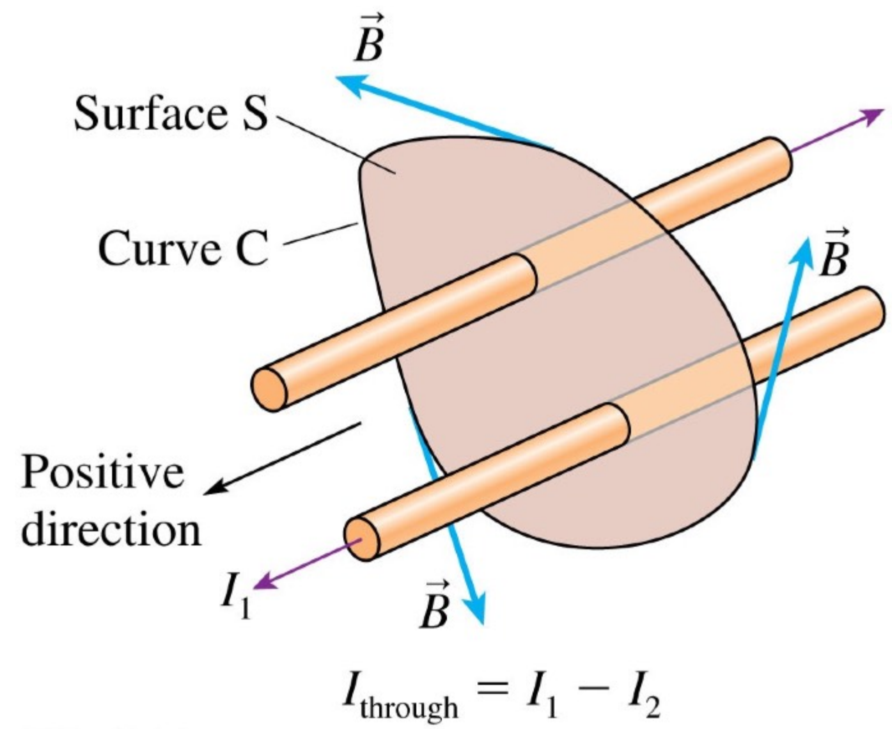
$$\vec{B}_B = \vec{B}_A - \frac{1}{c^2}\vec{v}_{BA} \times \vec{E}_A$$

$$\vec{E}_B = \vec{E}_A + \vec{v}_{BA} \times \vec{B}_A$$

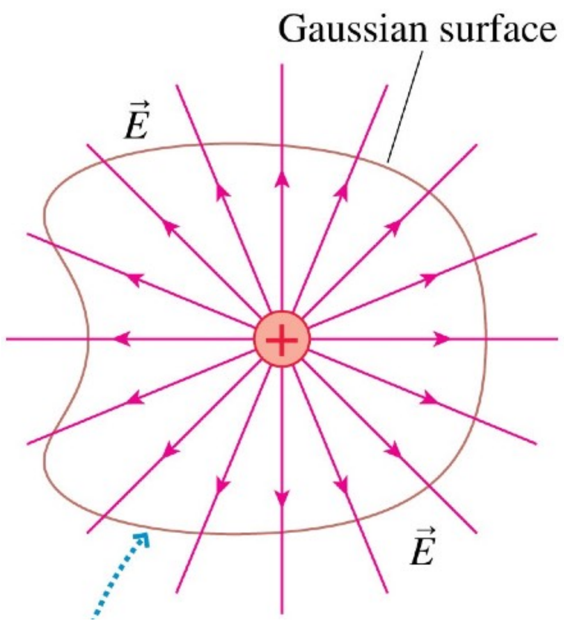
Summary of what we have learned so far

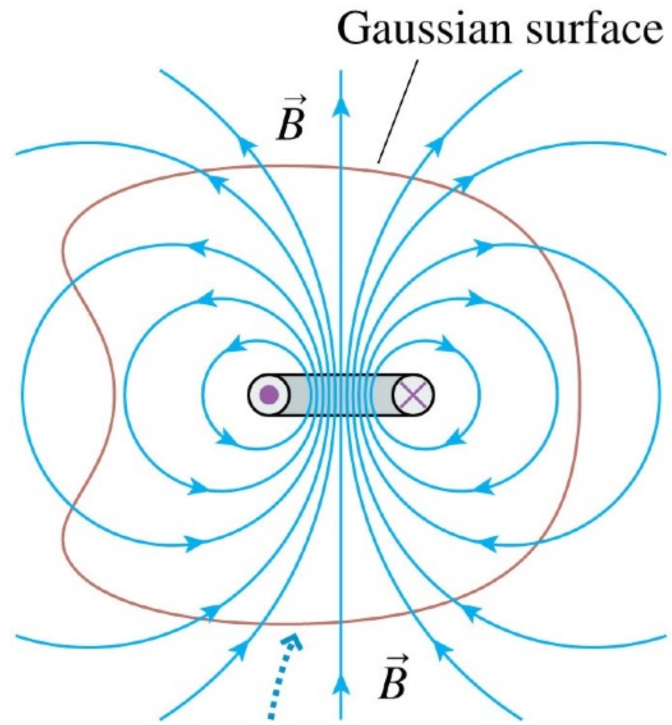


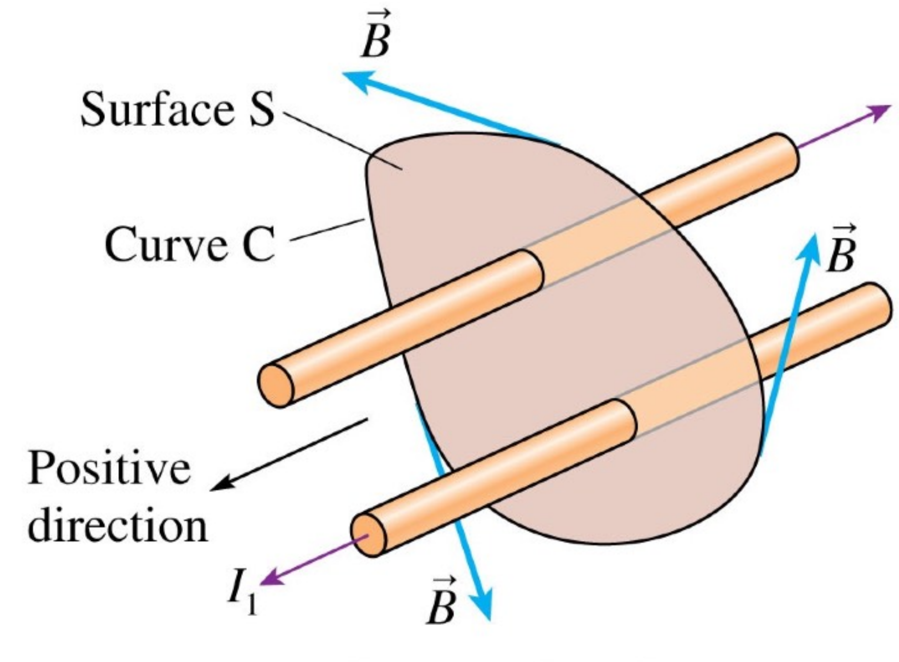




Summary of what we have learned so far



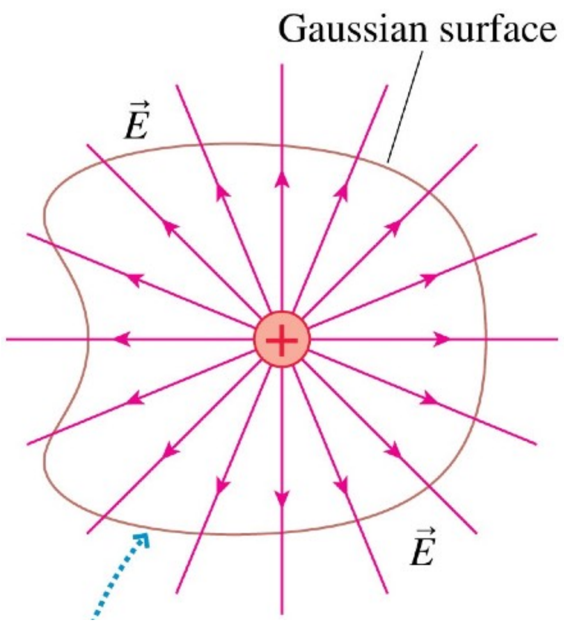


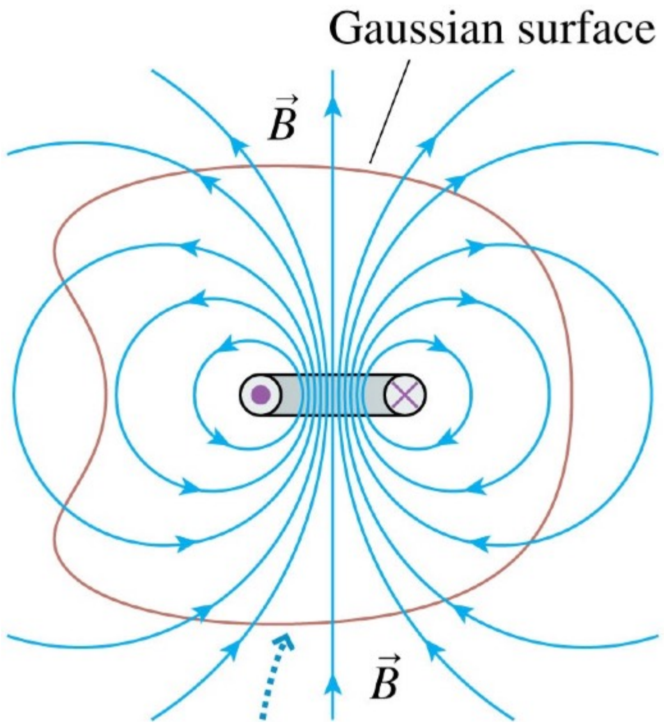


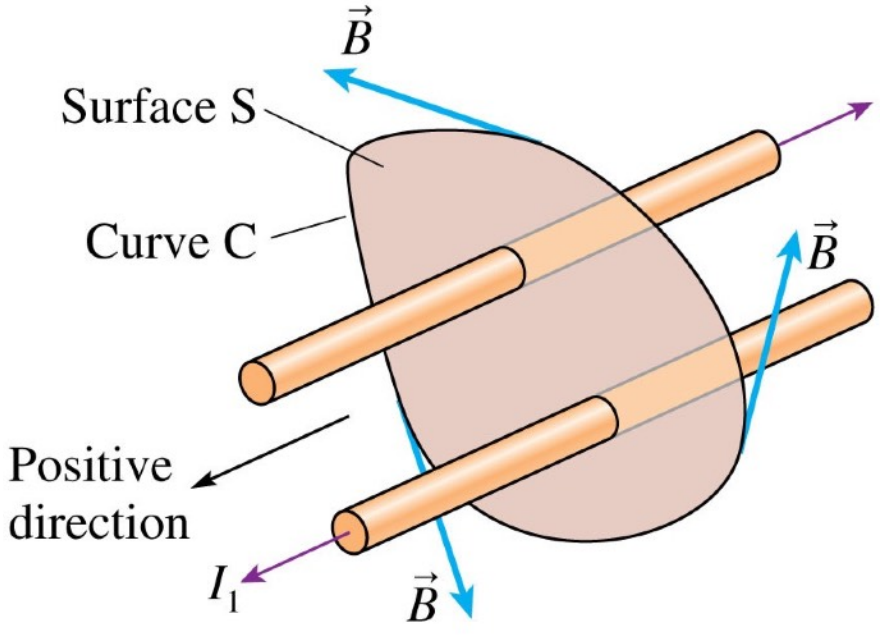
$I_{\text{through}} = I_1 - I_2$

$$(\Phi_m)_{\text{closed surface}} = \oint \vec{B} \cdot d\vec{A} = 0$$

Summary of what we have learned so far



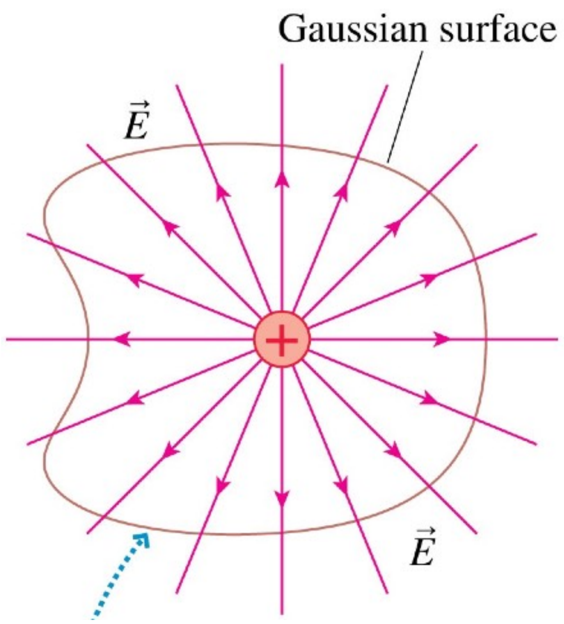


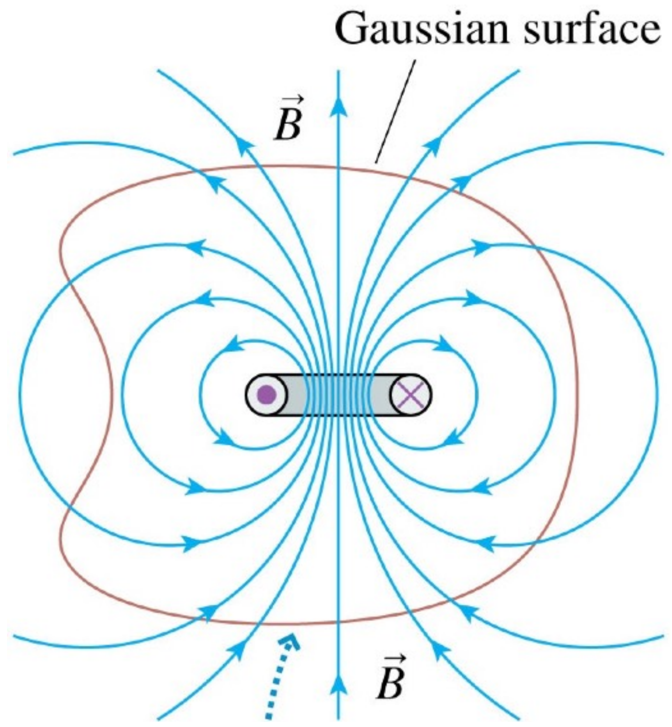


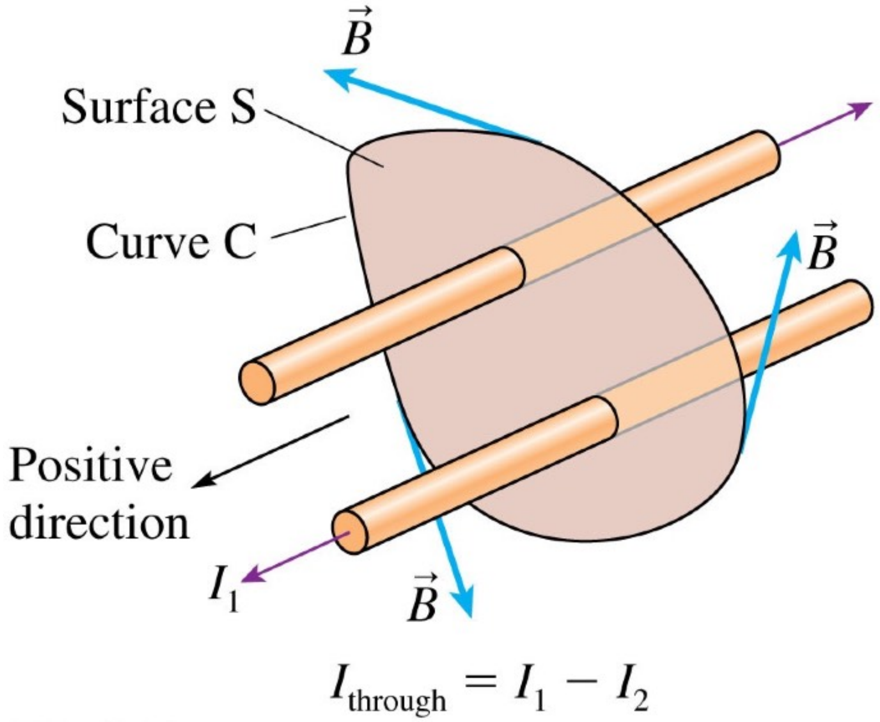
$$(\Phi_m)_{\text{closed surface}} = \oint \vec{B} \cdot d\vec{A} = 0$$

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 I_{\text{through}}$$

Summary of what we have learned so far







$$(\Phi_e)_{\text{closed surface}} = \oint \vec{E} \cdot d\vec{A} = \frac{Q_{\text{in}}}{\epsilon_0}$$

$$(\Phi_m)_{\text{closed surface}} = \oint \vec{B} \cdot d\vec{A} = 0$$

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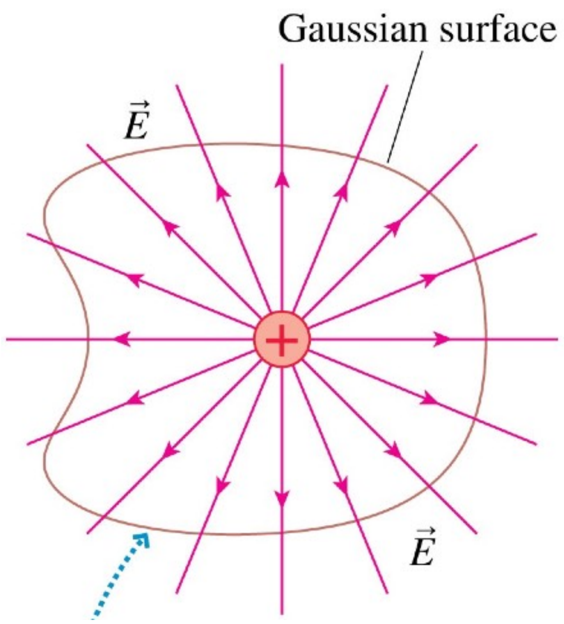
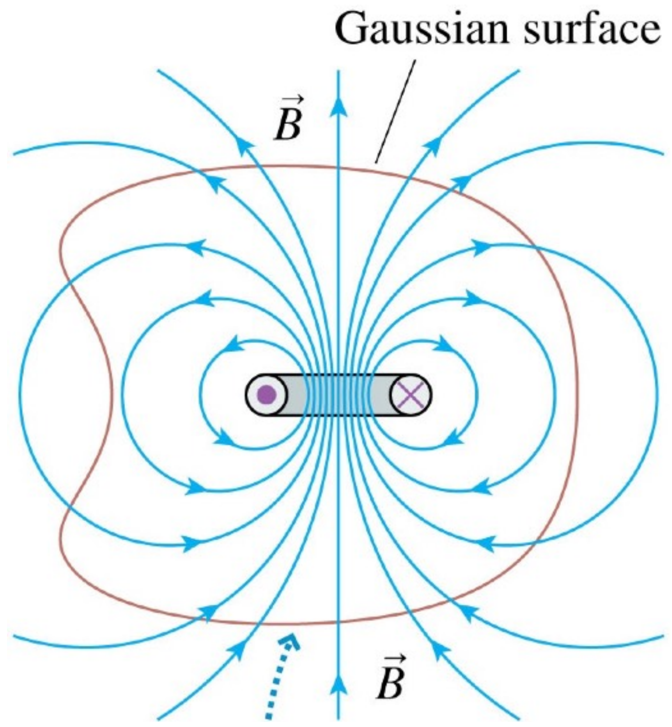
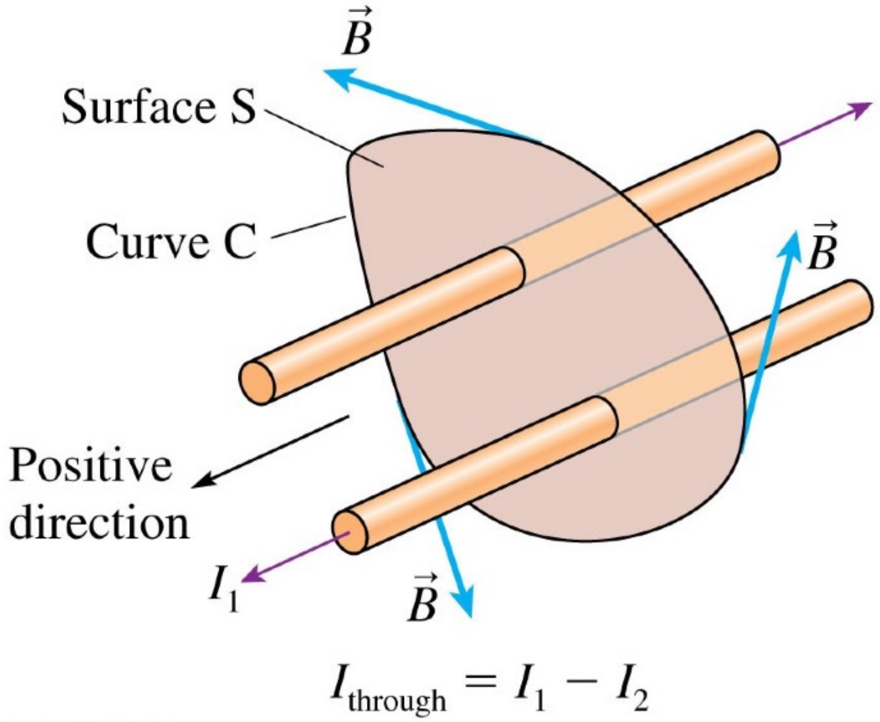
Summary of what we have learned so far







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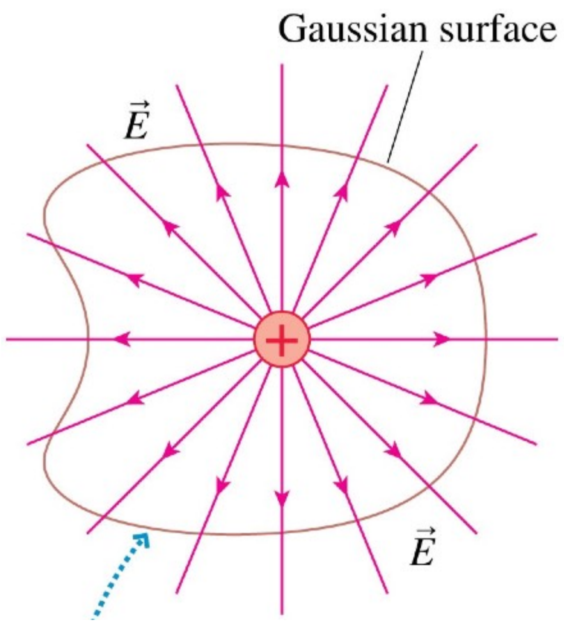
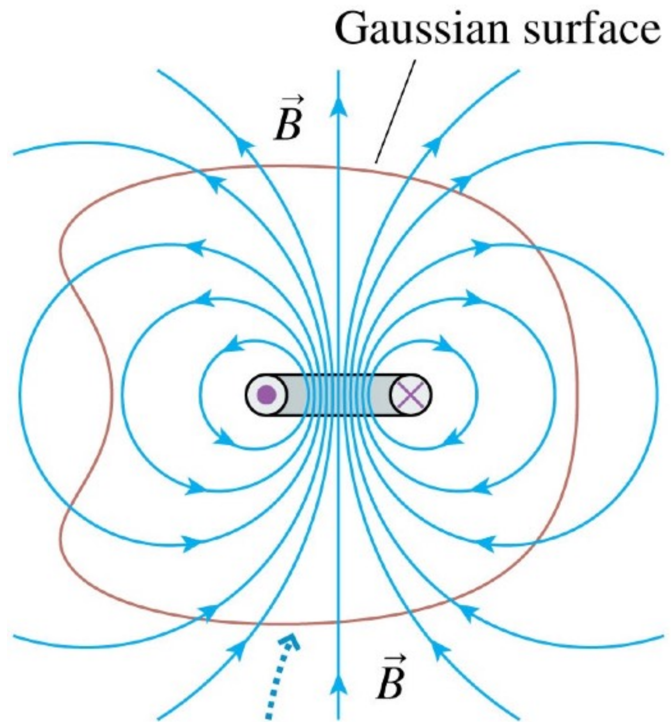
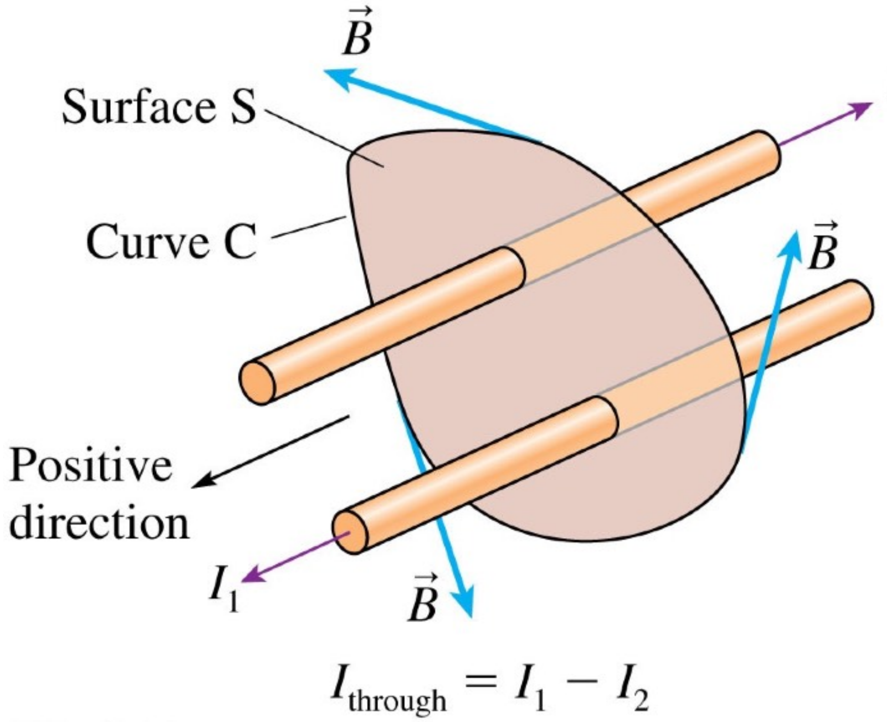
Faraday's Law

Summary of what we have learned so far







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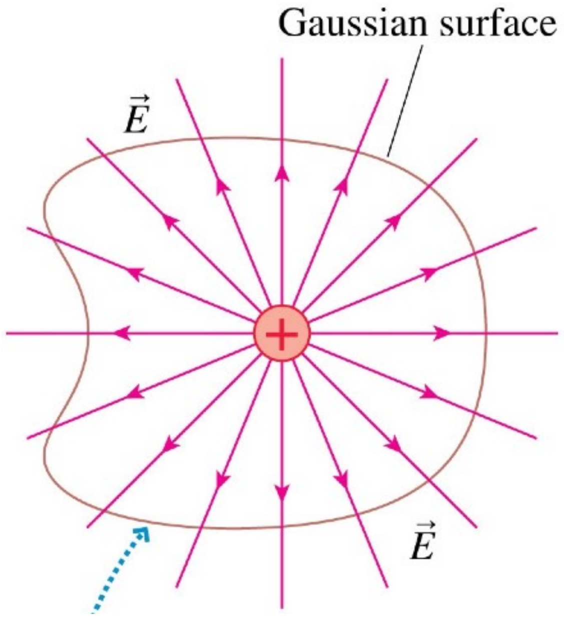
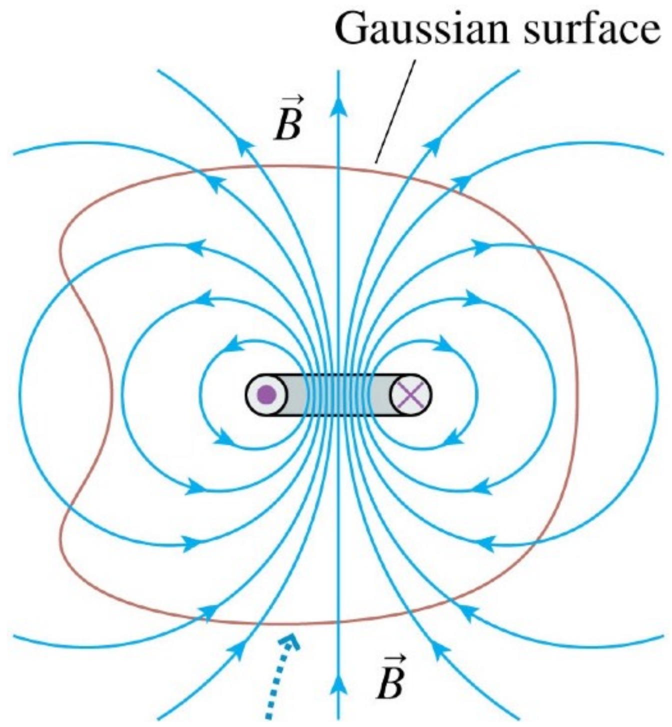
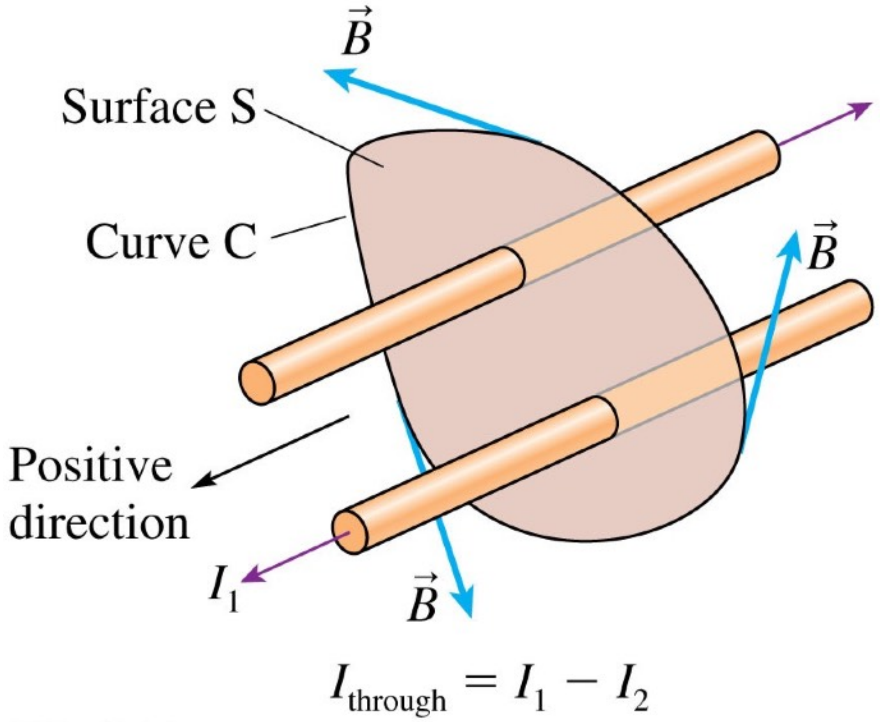
Faraday's Law

$$\mathcal{E} = \oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_m}{dt}$$

Summary of what we have learned so far







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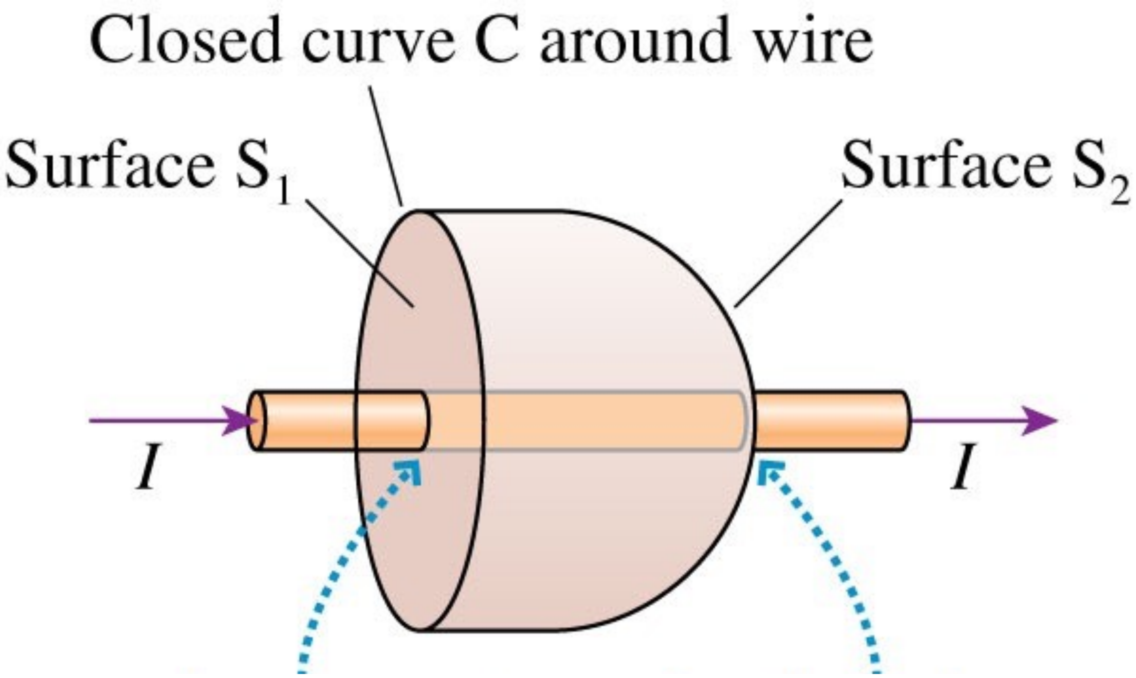
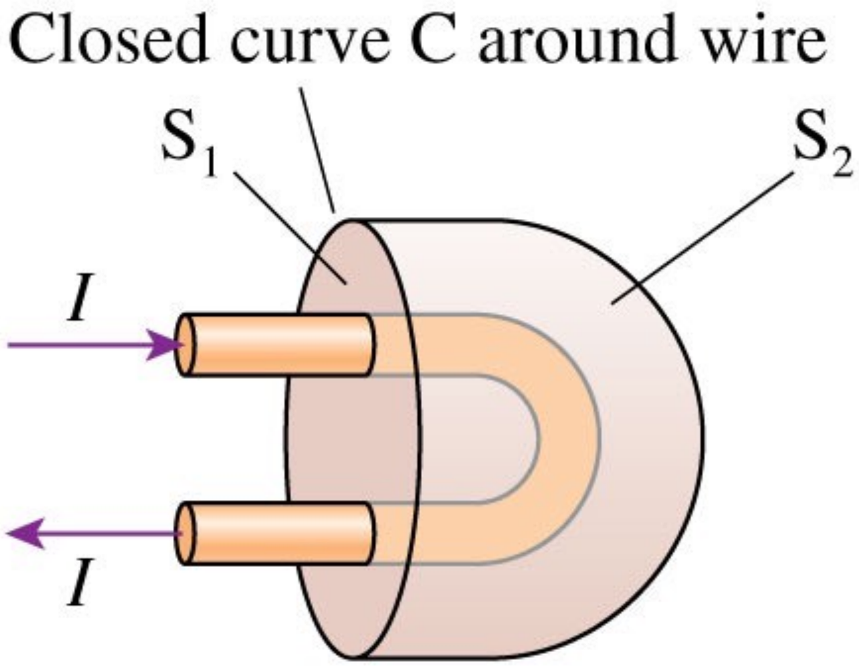
Faraday's Law

Fourth law with no picture

$$\mathcal{E} = \oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_m}{dt}$$

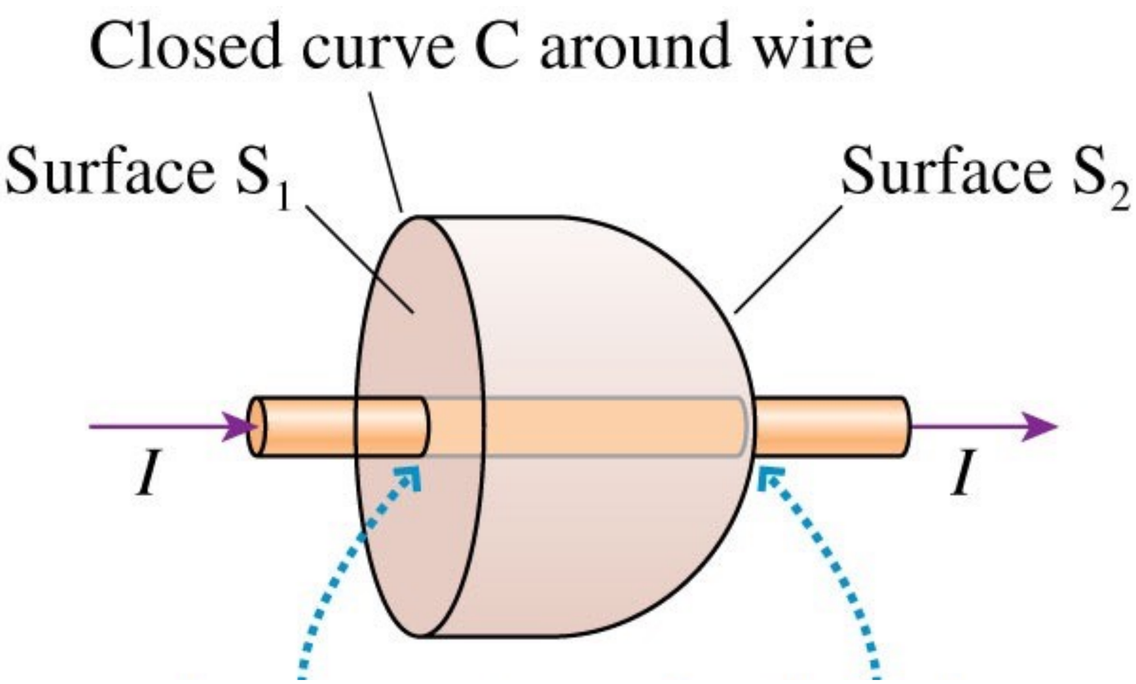
Back to Ampere's law

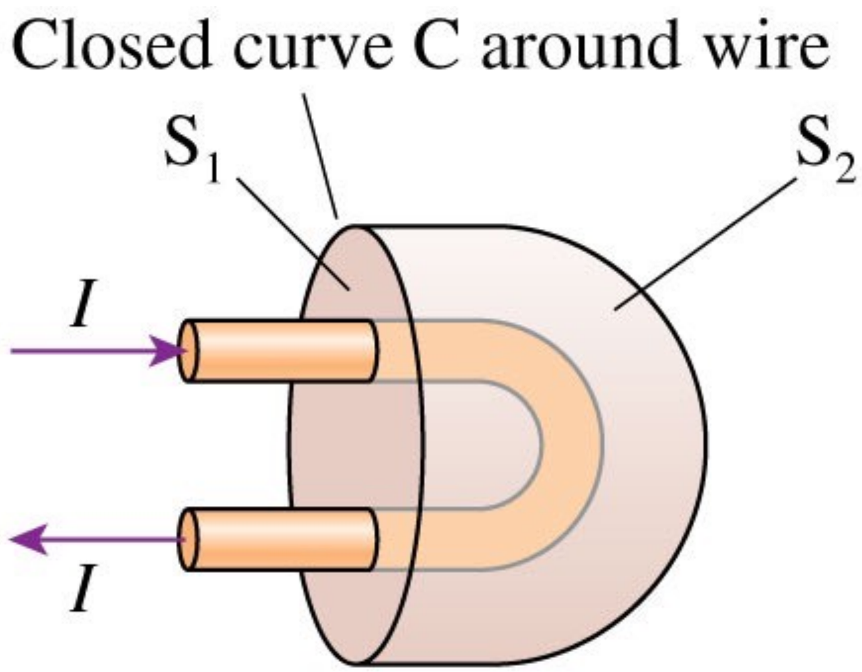




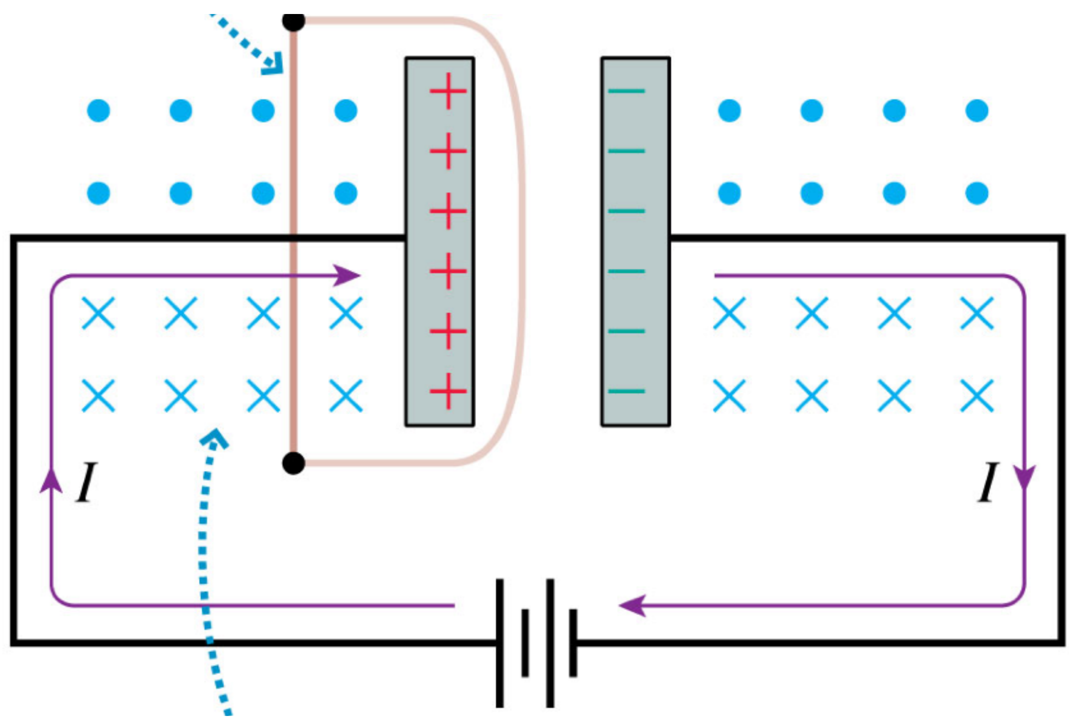
Back to Ampere's law

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 I_{\text{through}}$$





But what about…



Ampere's law not true?

But what about…

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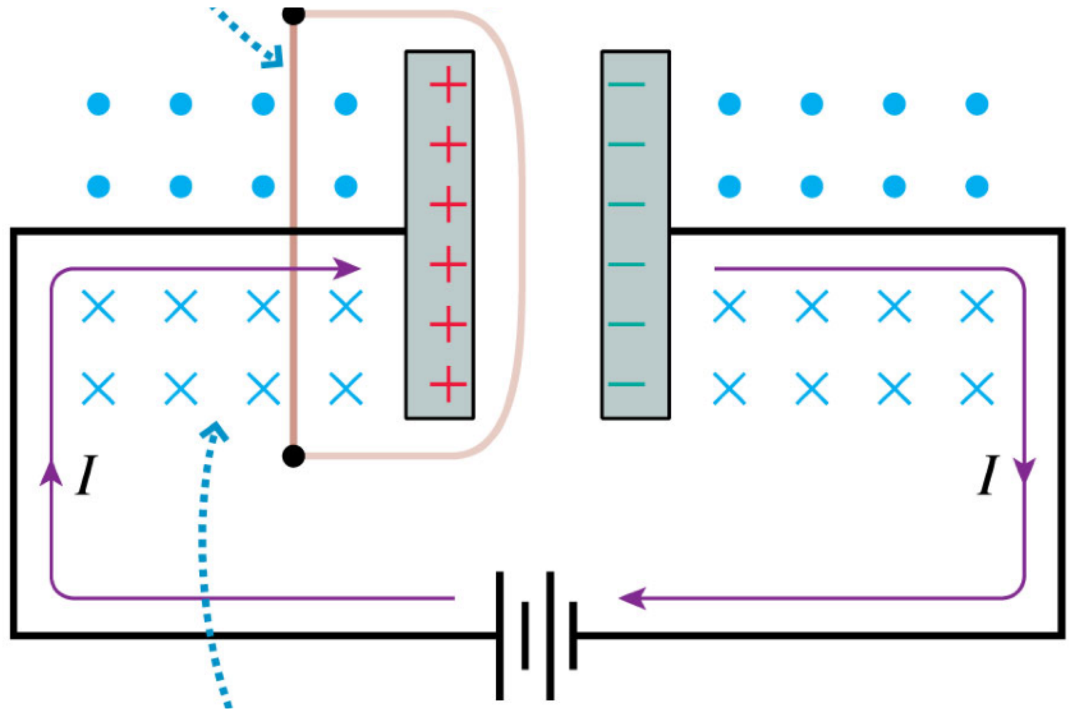

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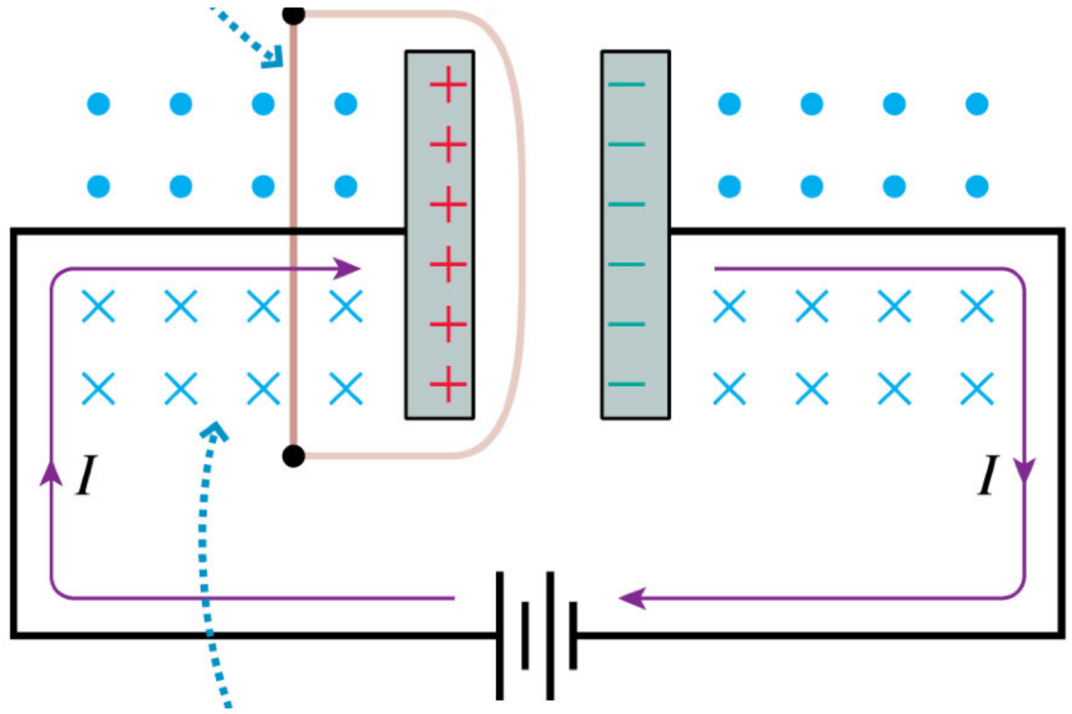
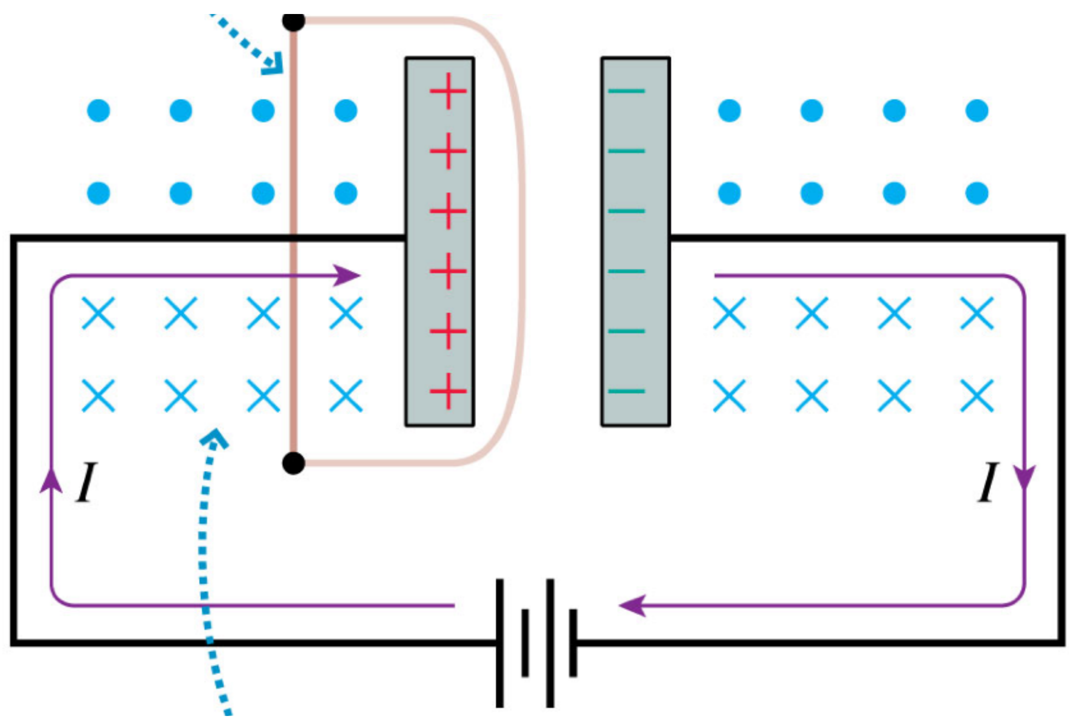


Ampere's law not true?

$$E = \frac{Q}{\epsilon_0 A}$$

But what about…

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 I_{\text{through}}$$

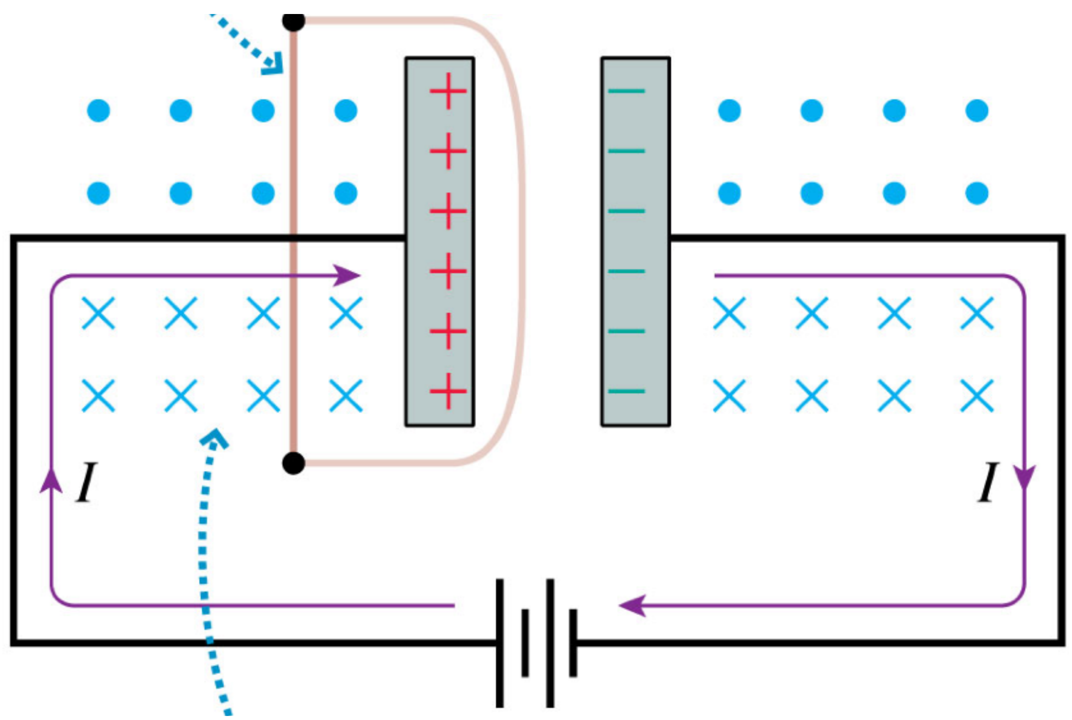


Ampere's law not true?

$$\Phi_e = EA \qquad E = \frac{Q}{\epsilon_0 A}$$

But what about…

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 I_{\text{through}}$$



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$$\Phi_e = EA \qquad E = \frac{Q}{\epsilon_0 A}$$

$$\frac{d\Phi_e}{dt} = \frac{1}{\epsilon_0}\frac{dQ}{dt} = \frac{I}{\epsilon_0}$$

But what about…

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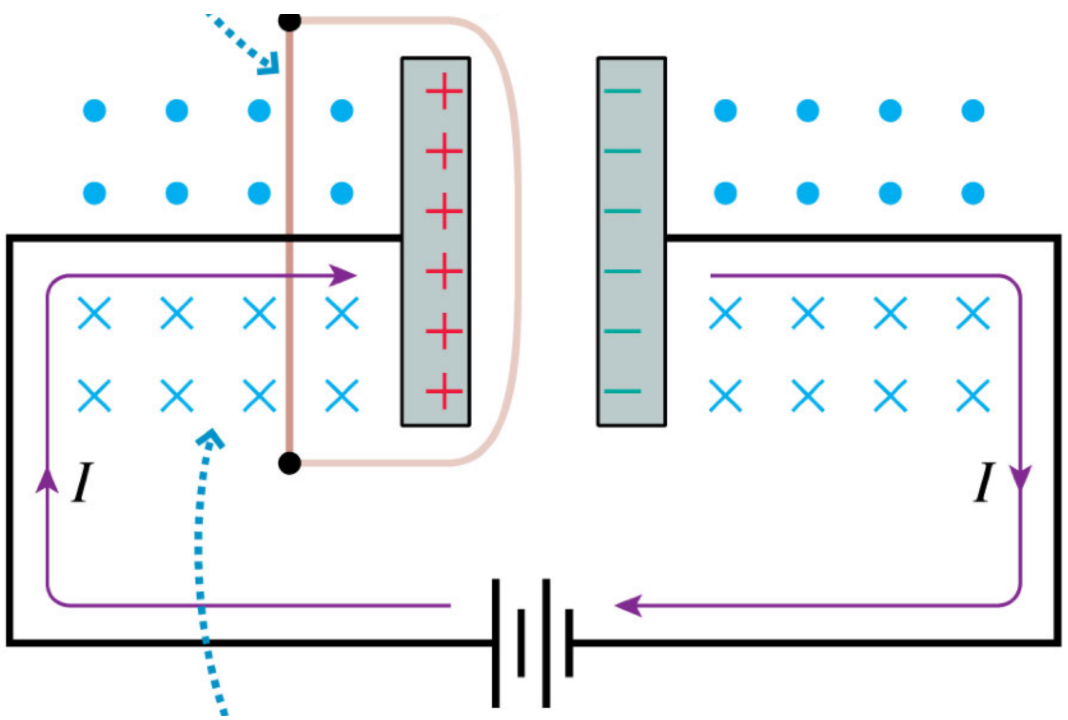

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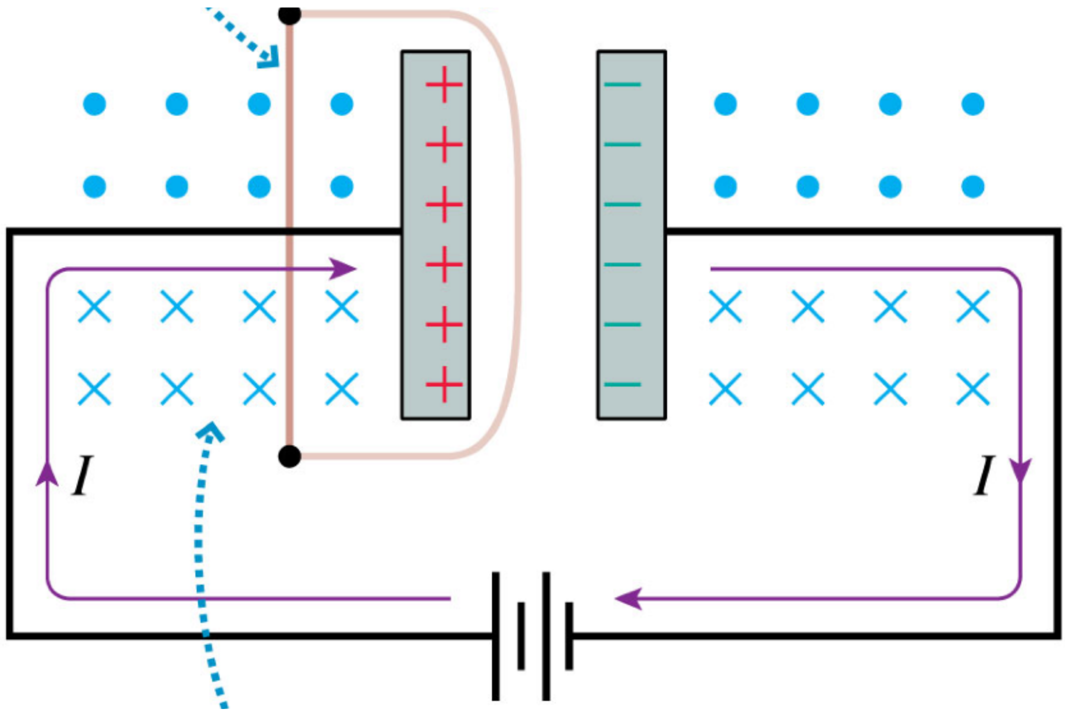
$$I_{\text{disp}} = \epsilon_0 \frac{d\Phi_e}{dt}$$

But what about…

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 I_{\text{through}}$$



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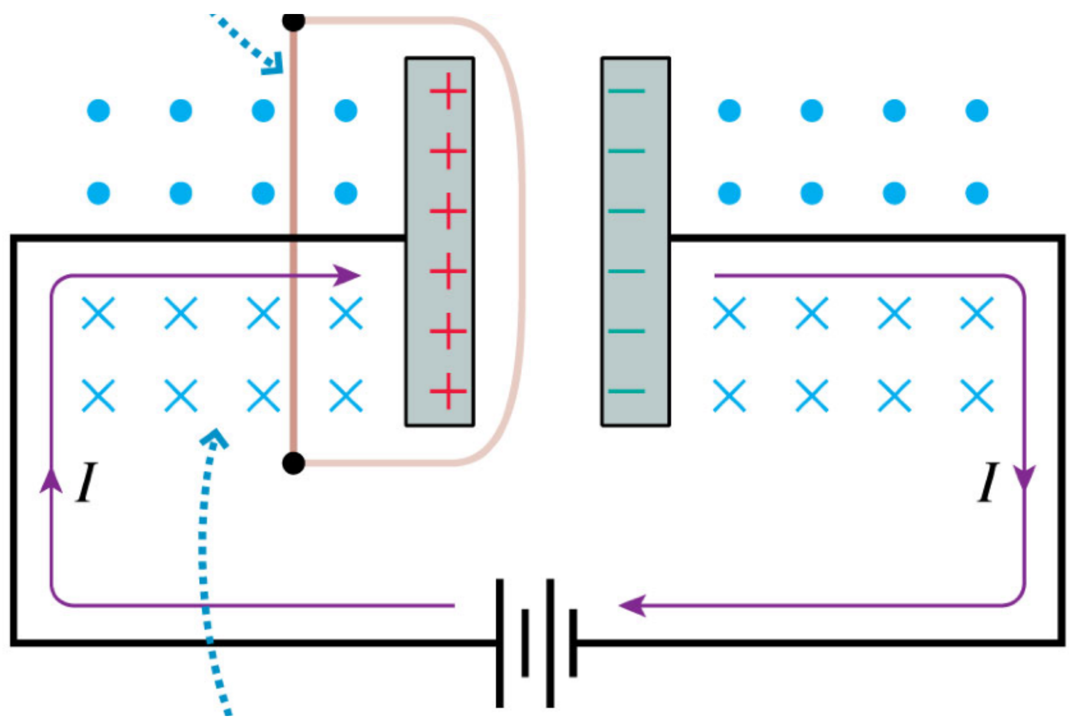
$$\boxed{\oint \vec{B} \cdot d\vec{s} = \mu_0(I_{\text{through}} + I_{\text{disp}}) = \mu_0(I_{\text{through}} + \epsilon_0 \frac{d\Phi_E}{dt})}$$

But what about…

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 I_{\text{through}}$$



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But what about…

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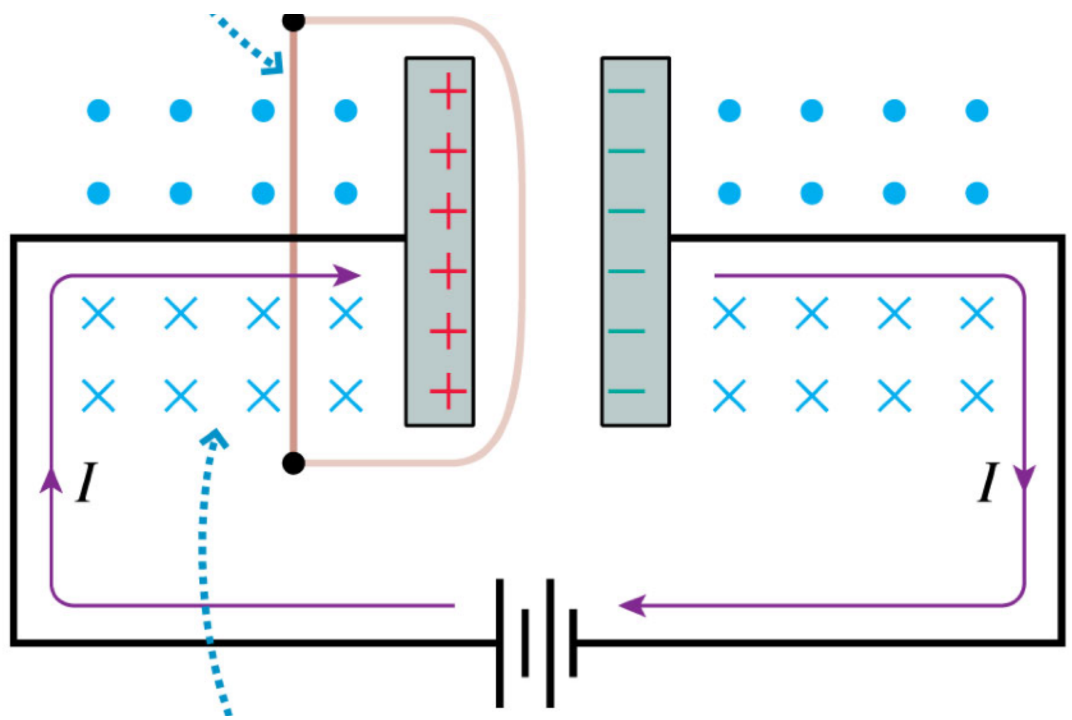

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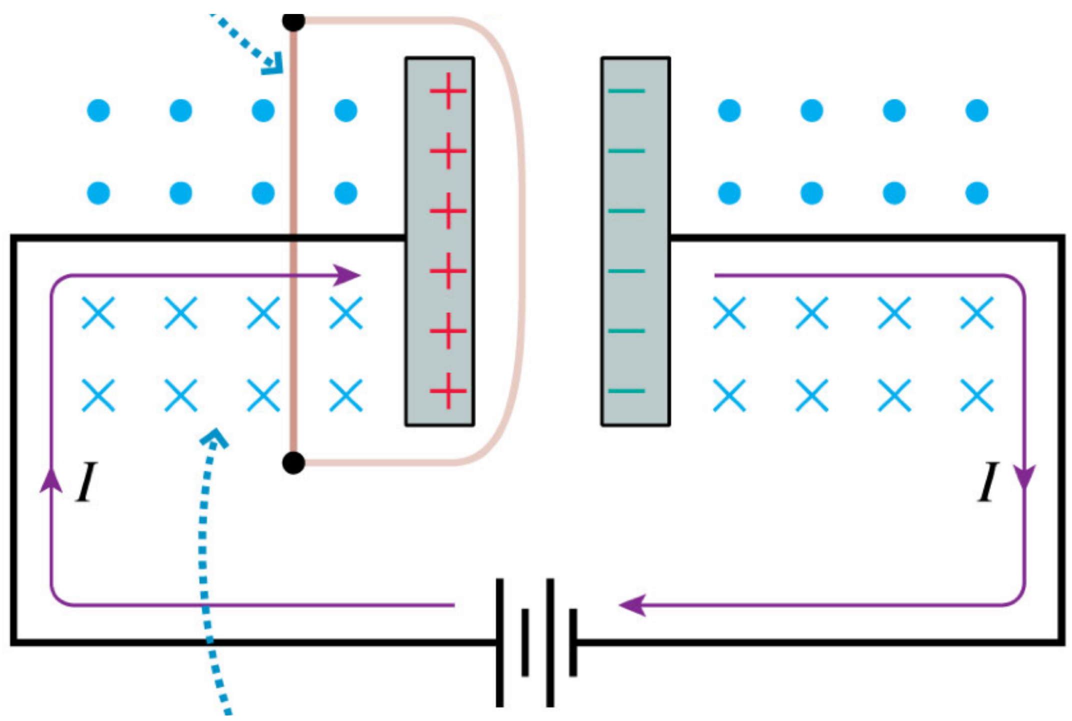
$$\boxed{\oint \vec{B} \cdot d\vec{s} = \mu_0 (I_{\text{through}} + I_{\text{disp}}) = \mu_0 \left(I_{\text{through}} + \epsilon_0 \frac{d\Phi_E}{dt}\right)}$$

Ampere-Maxwell equation

But what about…

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 I_{\text{through}}$$



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Ampere-Maxwell equation

This is kind of like a current…

Summary

How do you create an electric field?

How do you create a magnetic field?

$$\boxed{\oint \vec{B} \cdot d\vec{s} = \mu_0 \left(I_{\text{through}} + \epsilon_0 \frac{d\Phi_{\text{E}}}{dt} \right)}$$

Summary

How do you create an electric field?

How do you create a magnetic field?

$$\boxed{\vec{E} = \frac{kq}{r^2}\hat{r}}$$

$$\boxed{\oint \vec{B} \cdot d\vec{s} = \mu_0 \left(I_{\text{through}} + \epsilon_0 \frac{d\Phi_{\text{E}}}{dt} \right)}$$

Summary

How do you create an electric field?

$$\boxed{\vec{E} = \frac{kq}{r^2}\hat{r}}$$

$$\boxed{\begin{aligned} \mathcal{E} &= \frac{d\Phi}{dt} \\ \int \vec{E} \cdot d\vec{s} &= \frac{d\Phi}{dt} \end{aligned}}$$

How do you create a magnetic field?

$$\boxed{\oint \vec{B} \cdot d\vec{s} = \mu_0 \left(I_{\text{through}} + \epsilon_0 \frac{d\Phi_{\text{E}}}{dt} \right)}$$

Summary

How do you create an electric field?

How do you create a magnetic field?

$$\boxed{\vec{E} = \frac{kq}{r^2}\hat{r}}$$

Created by charge/ moving charge!

$$\boxed{\begin{aligned} \mathcal{E} &= \frac{d\Phi}{dt} \\ \int \vec{E} \cdot d\vec{s} &= \frac{d\Phi}{dt} \end{aligned}}$$

$$\boxed{\oint \vec{B} \cdot d\vec{s} = \mu_0 \left(I_{\text{through}} + \epsilon_0 \frac{d\Phi_{\text{E}}}{dt} \right)}$$

Summary

How do you create an electric field?

How do you create a magnetic field?

$$\boxed{\vec{E} = \frac{kq}{r^2}\hat{r}}$$

Created by charge/ moving charge!

$$\boxed{\begin{aligned} \mathcal{E} &= \frac{d\Phi}{dt} \\ \int \vec{E} \cdot d\vec{s} &= \frac{d\Phi}{dt} \end{aligned}}$$

Charge not needed to create field!

$$\boxed{\oint \vec{B} \cdot d\vec{s} = \mu_0 \left(I_{\text{through}} + \epsilon_0 \frac{d\Phi_{\text{E}}}{dt} \right)}$$

Summary

How do you create an electric field?

$$\boxed{\vec{E} = \frac{kq}{r^2}\hat{r}}$$

Created by charge/ moving charge!

$$\boxed{\begin{aligned}\mathcal{E} &= \frac{d\Phi}{dt} \\ \int \vec{E}\cdot d\vec{s} &= \frac{d\Phi}{dt}\end{aligned}}$$

Charge not needed to create field!

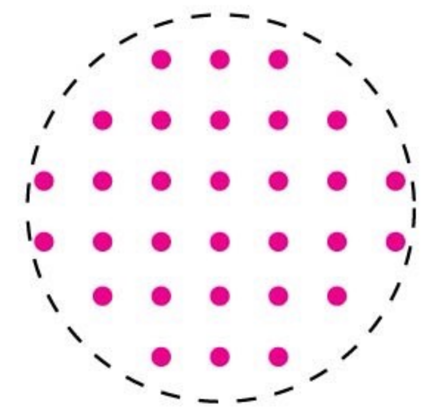
How do you create a magnetic field?

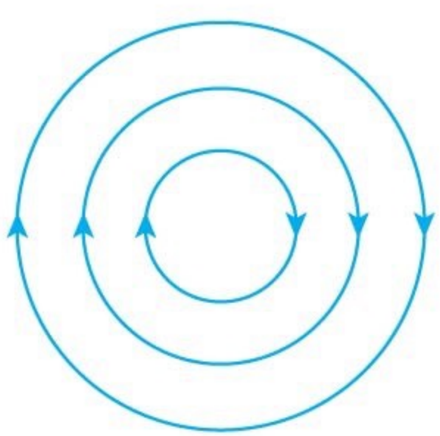
$$\boxed{\begin{aligned}\vec{B} &= \frac{\mu_0}{4\pi}\frac{q\vec{v}\times\hat{r}}{r^2} \\ \vec{B} &= \frac{\mu_0}{4\pi}\frac{I\vec{\Delta s}\times\hat{r}}{r^2}\end{aligned}}$$

$$\boxed{\oint \vec{B}\cdot d\vec{s} = \mu_0\left(I_{\text{through}} + \epsilon_0\frac{d\Phi_{\text{E}}}{dt}\right)}$$

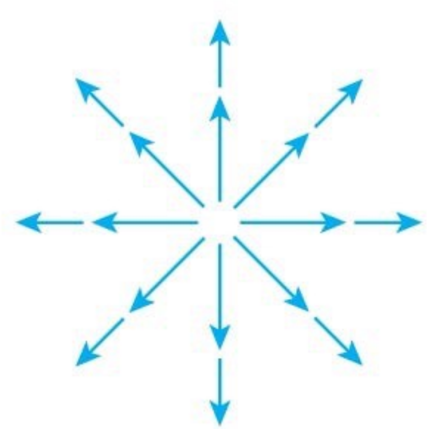
Question #18

The electric field is increasing.
Which is the induced magnetic field?

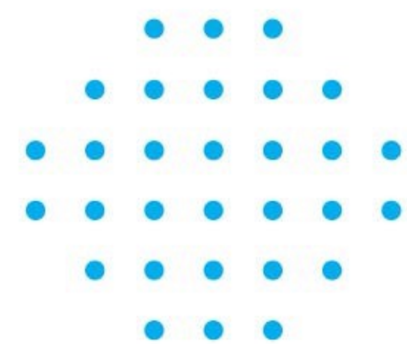




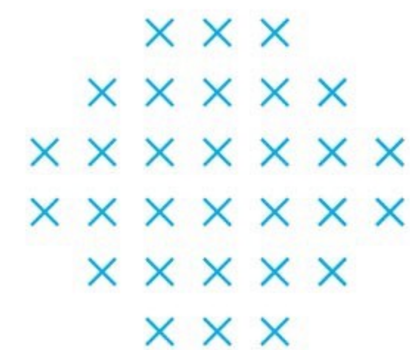
E



A

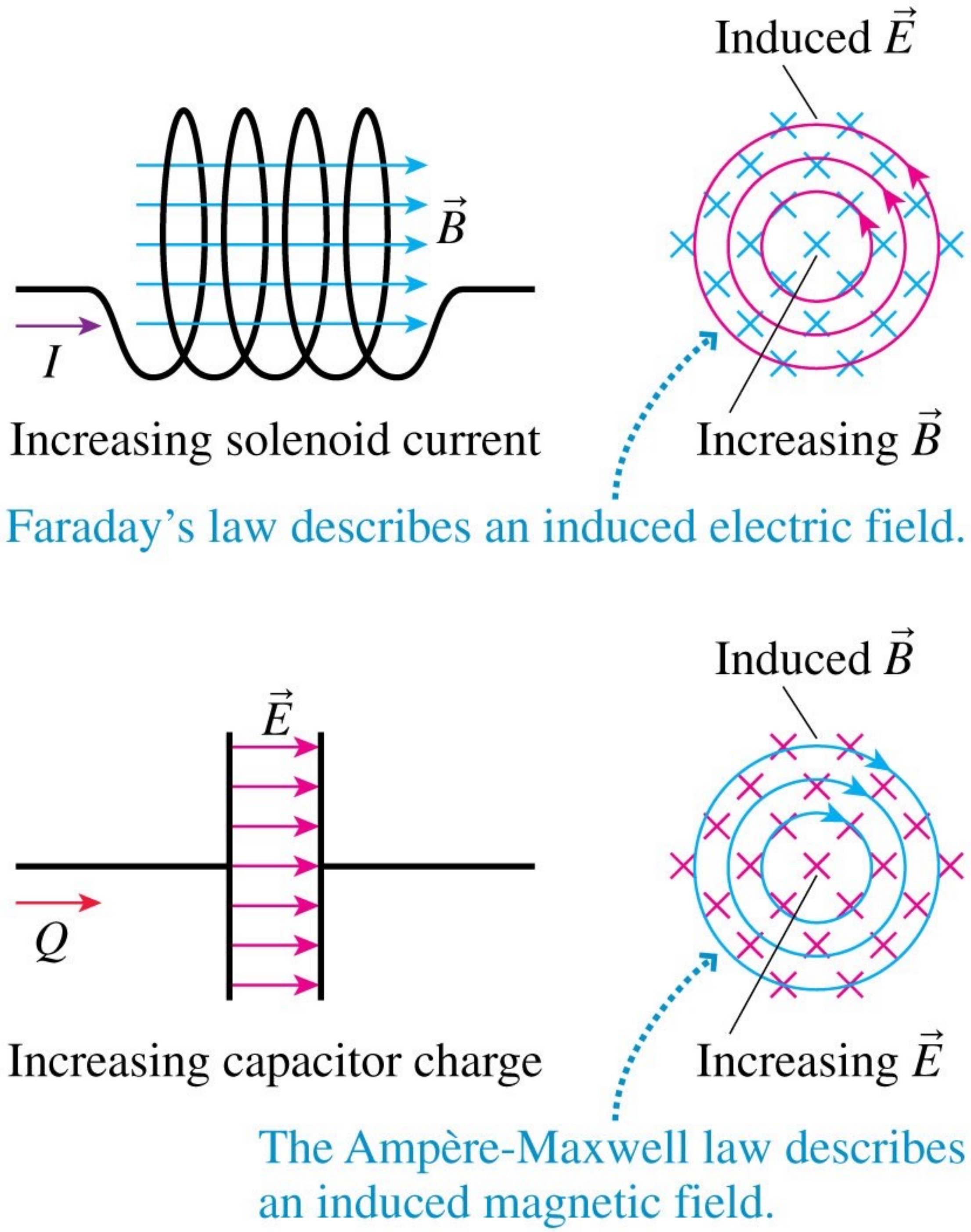


B



C

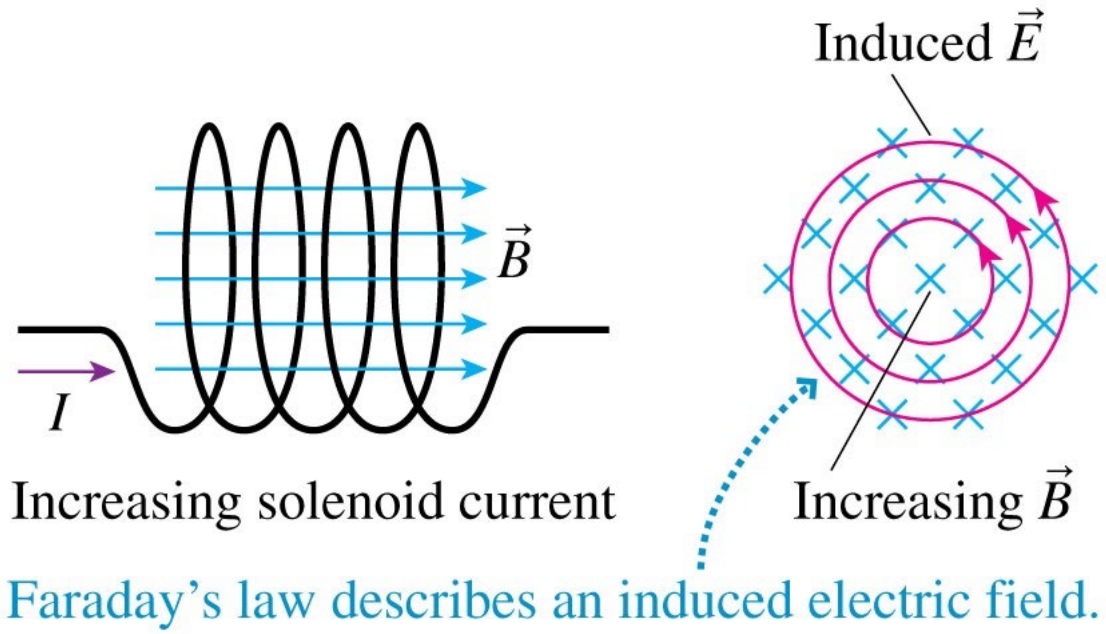
Induced fields



notice the sign difference

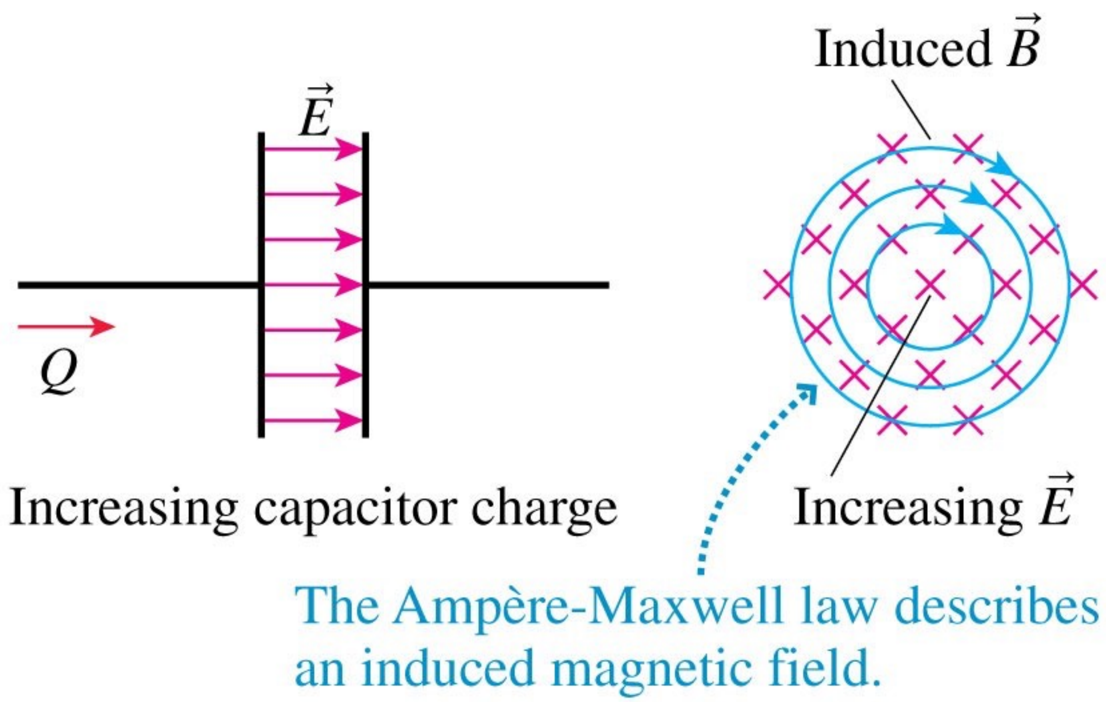
$$\oint \vec{B} \cdot d\vec{s} = \mu_0 (I_{\text{through}} + \epsilon_0 \frac{d\Phi_E}{dt})$$

Induced fields



$$\mathcal{E} = \oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_{\mathrm{m}}}{dt}$$

notice the sign difference



$$\oint \vec{B} \cdot d\vec{s} = \mu_0 (I_{\mathrm{through}} + \epsilon_0 \frac{d\Phi_E}{dt})$$

Summary

State in words and in math, the meaning of these laws.

Gauss's Law

Gauss's Law for magnetism

Faraday's Law

Ampere-Maxwell

Lorentz force law

Summary

State in words and in math, the meaning of these laws.

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Gauss's Law for magnetism

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$$F = q(\vec{E} + \vec{v} \times \vec{B})$$

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