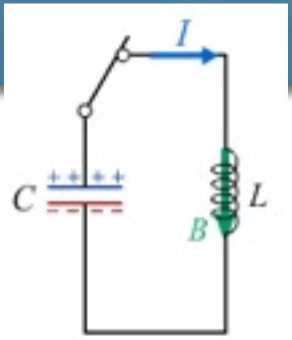
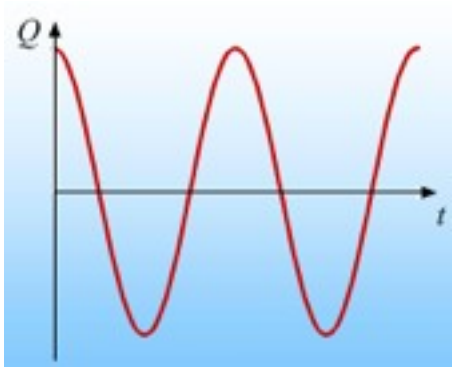
Electricity & Magnetism
Lecture 19



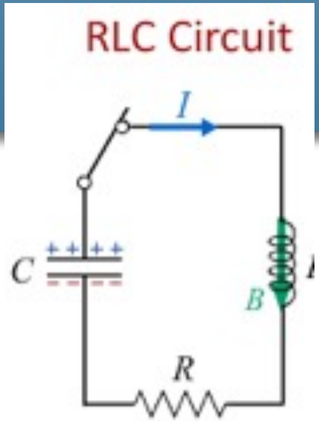
Today's Concepts:

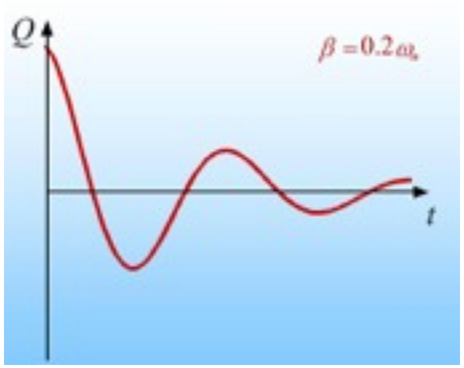


A) Oscillation Frequency

B) Energy

C) Damping





Confused — Confident

I am ...

A. Confused

B. Somewhat Confused

C. So-so

D. Somewhat Confident

E. Confident

Your Comments

"All of this stuff, I wish we could go slower but I know we cant."

TOO TRUE: Hang in there, we'll do our best to work on the issues….

"Differential equations have taken over my life. I'm not sure I approve."

"There are a lot of formulas in this section"

"Please explain the meaning of cos(ωt + x)"

Differential Equations Do Determine Much Behaviour in Physics. We will show corresponding equations in mechanics today

"Why do capacitors start off with a charge of zero when the switch is opened? shouldn't they start off with charge? "

It all depends on how the circuit was started. You have to determine the initial conditions from the problem statement

Walking home from the mechanics final last semester I though I was done with oscillatory motion for life. Never have I been so wrong...

That's right!

Some Practical Test Stuff

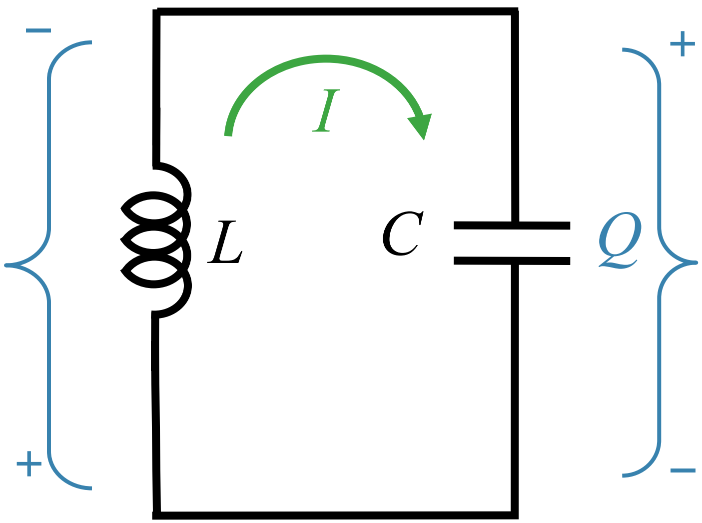
Practical Test is on Friday, July 5

- We will have 2 practise sessions: Friday and Next Wednesday
- Covers DC Circuits and the Oscilloscope (LC or RC Circuit)
- 50 min each — We will divide class into two halves.
  - (those who don't have class after this should sign up for the later one.)
- smartPhysics will continue Fri and Wed covering these topics theoretically
- Practise exam is here:
- You may also practise on circuits of your own (eg. LCR circuits and resonance)

LC Circuit

"tank"

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



$$V_C = \frac{Q}{C}$$

Circuit Equation: $\frac{Q}{C} + L\frac{dI}{dt} = 0$

$$I = \frac{dQ}{dt} \rightarrow \frac{d^2Q}{dt^2} = -\frac{Q}{LC} \rightarrow \frac{d^2Q}{dt^2} = -\omega^2 Q$$

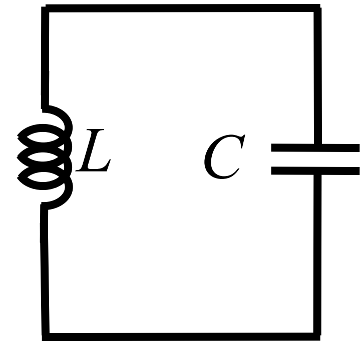
where

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

$$m \leftrightarrow L$$

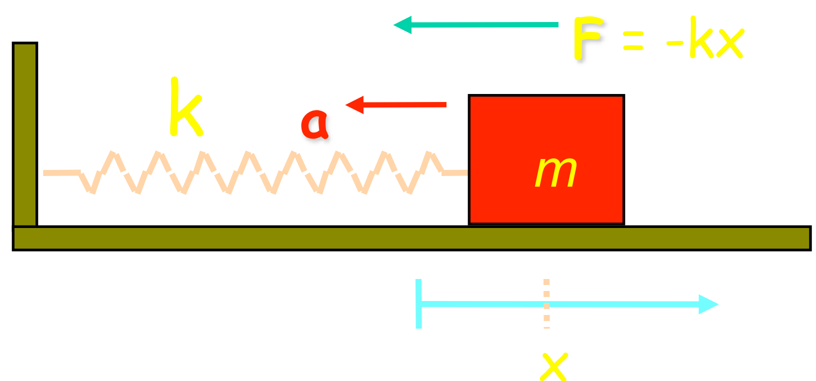
$$\frac{d^2Q}{dt^2} = -\omega^2 Q$$

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



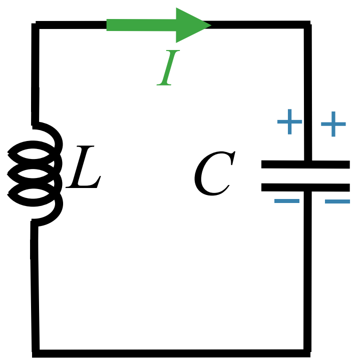
$$\frac{d^2x}{dt^2} = -\omega^2 x$$

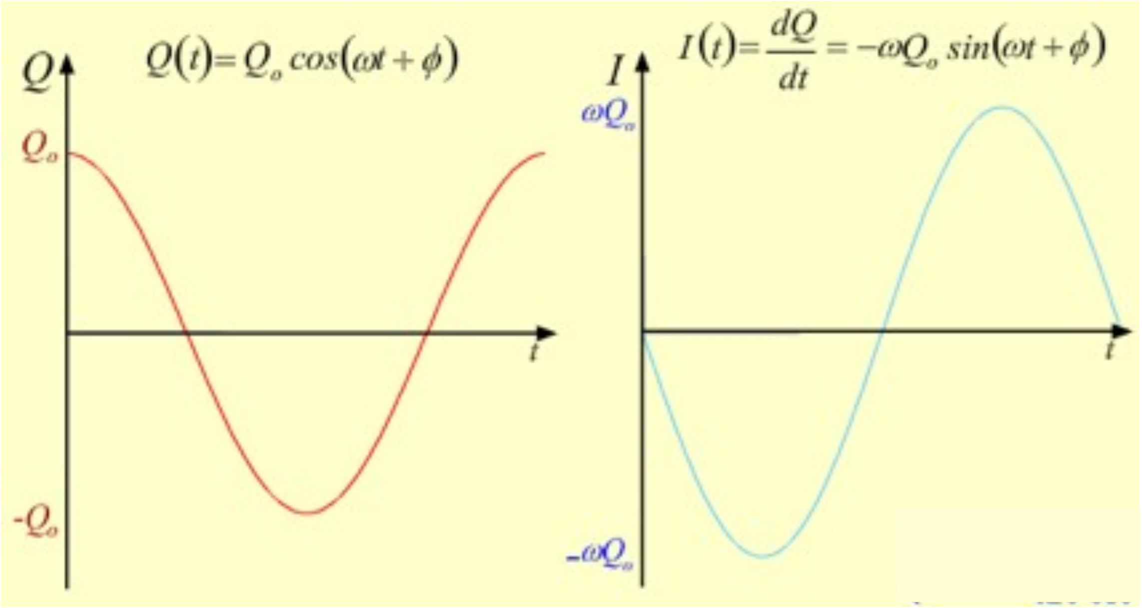
$$\omega = \sqrt{\frac{k}{m}}$$



Same thing if we notice that $k \leftrightarrow \frac{1}{C}$ and $m \leftrightarrow L$

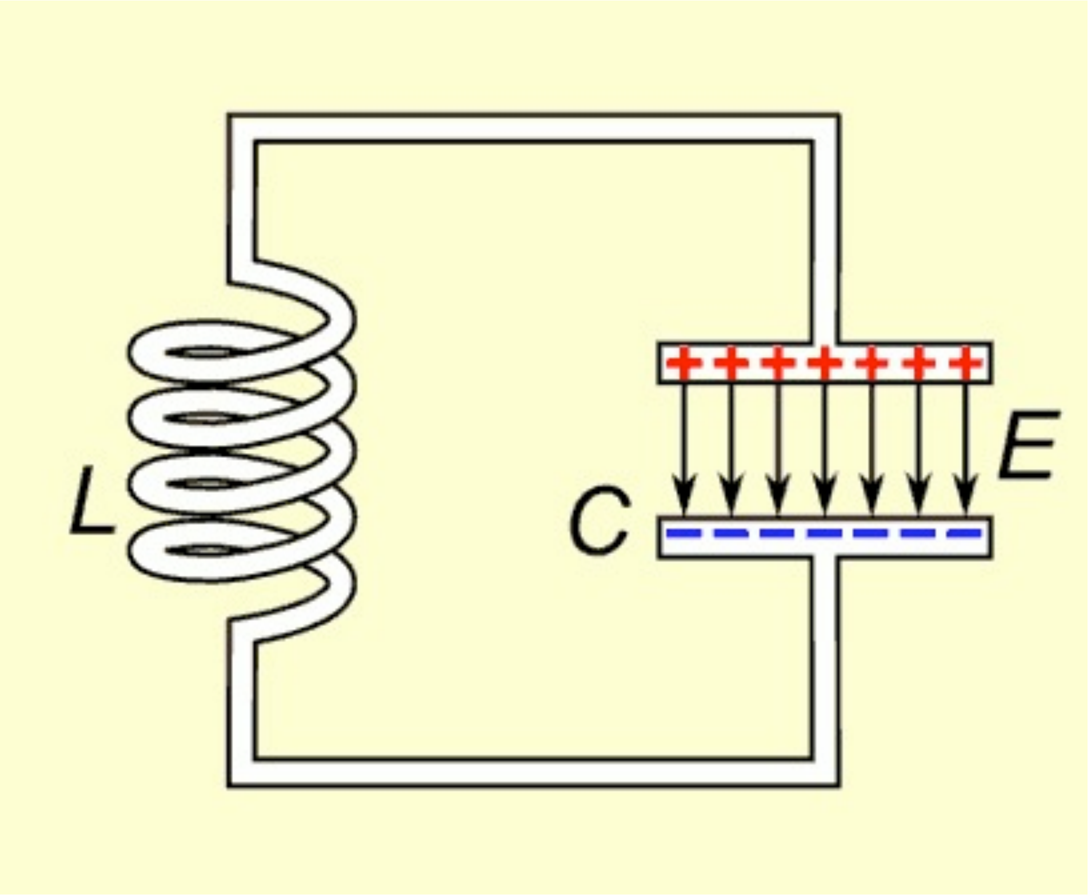
Time Dependence





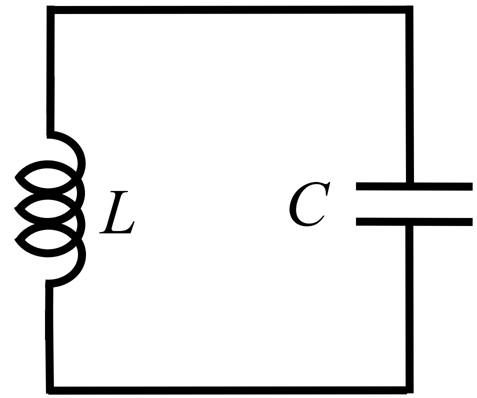
Wikipedia Animation

"LC Circuit"



CheckPoint 2

At time $t = 0$ the capacitor is fully charged with Q_{max} and the current through the circuit is 0.



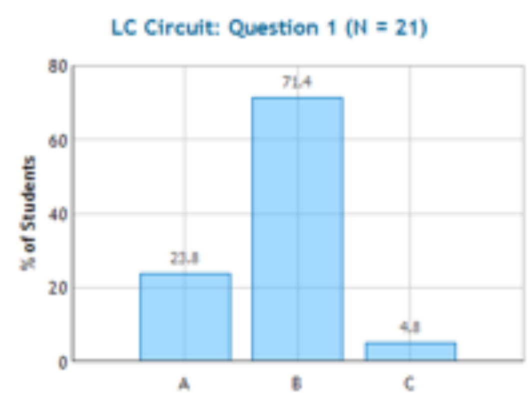
What is the potential difference across the inductor at $t = 0$?

A) $V_L = 0$

B) $V_L = Q_{max}/C$ since $V_L = V_C$

C) $V_L = Q_{max}/2C$

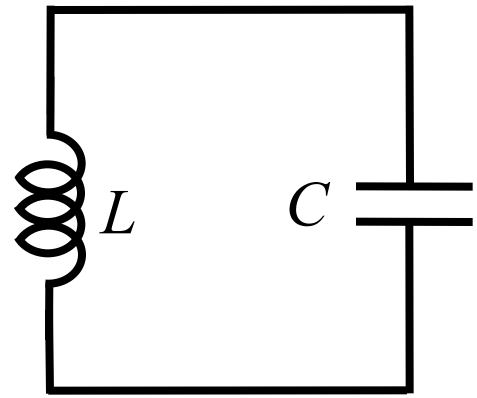
The voltage across the capacitor is Q_{max}/C Kirchhoff's Voltage Rule implies that must also be equal to the voltage across the inductor



Pendulum.

CheckPoint 4

At time $t = 0$ the capacitor is fully charged with Q_{max} and the current through the circuit is 0.

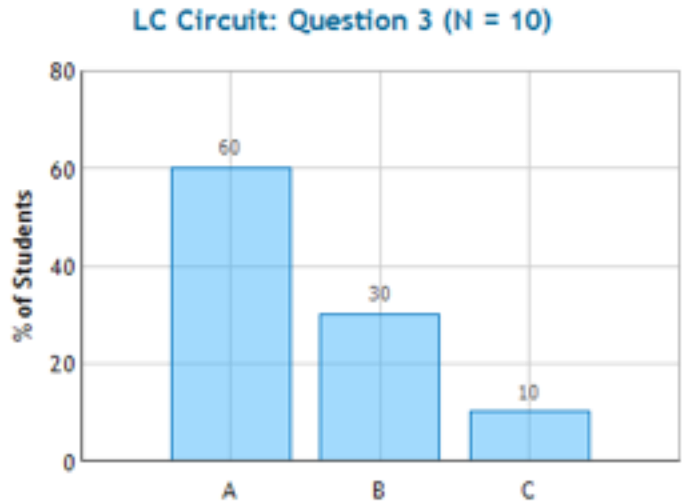


What is the potential difference across the inductor when the current is maximum?

A) $V_L = 0$

B) $V_L = Q_{max}/C$

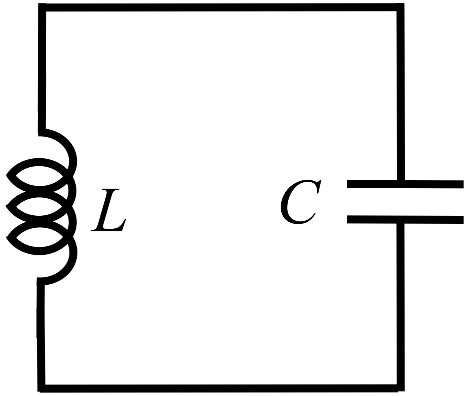
C) $V_L = Q_{max}/2C$



dI/dt is zero when current is maximum

CheckPoint 6

At time $t = 0$ the capacitor is fully charged with Q_{max} and the current through the circuit is 0.



How much energy is stored in the capacitor when the current is a maximum ?

A) $U = Q_{max}^2/(2C)$

B) $U = Q_{max}^2/(4C)$

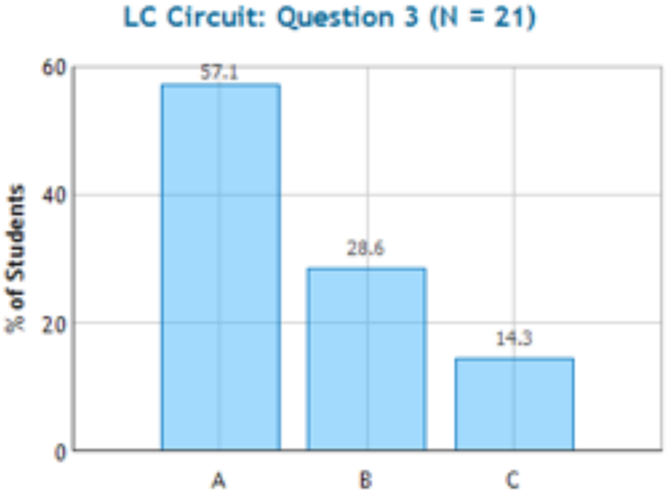
C) $U = 0$

Total Energy is constant!

$U_{Lmax} = ½ LI_{max}^2$

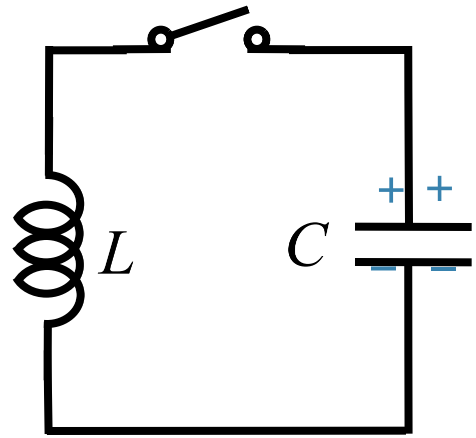
$U_{Cmax} = Q_{max}^2/2C$

$I = max$ when $Q = 0$



CheckPoint 8

The capacitor is charged such that the top plate has a charge $+Q_0$ and the bottom plate $-Q_0$. At time $t = 0$, the switch is closed and the circuit oscillates with frequency $\omega = 500$ radians/s.



$L = 4 \times 10^{-3}$ H

$\omega = 500$ rad/s

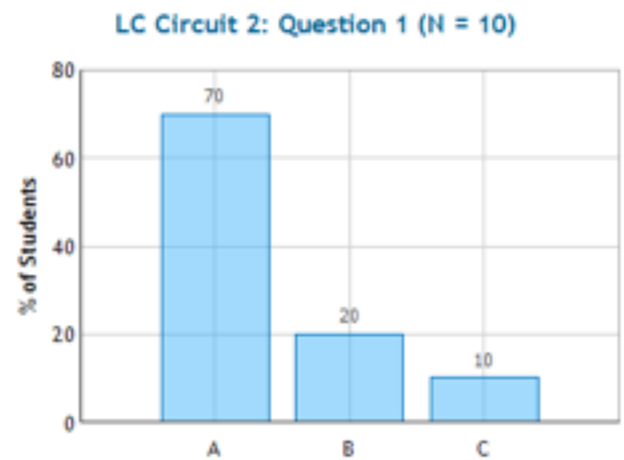
What is the value of the capacitor C?

A) $C = 1 \times 10^{-3}\ F$

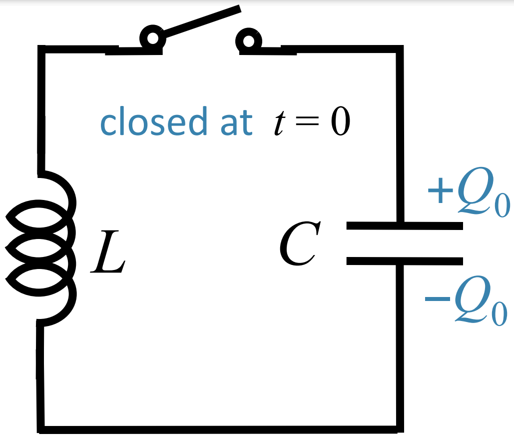
B) $C = 2 \times 10^{-3}\ F$

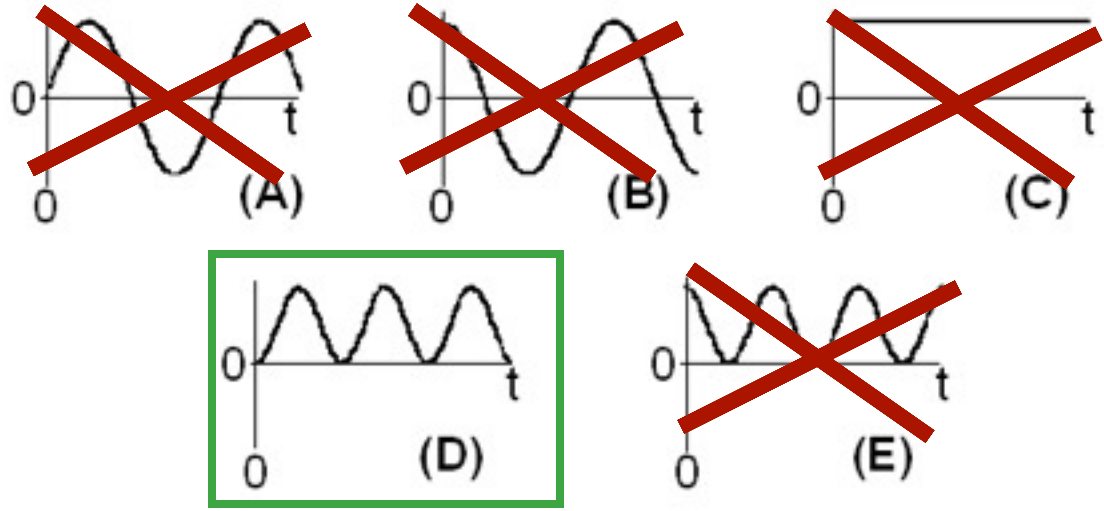
C) $C = 4 \times 10^{-3}\ F$

$$\omega = \frac{1}{\sqrt{LC}} \rightarrow C = \frac{1}{\omega^2 L} = \frac{1}{(25\times10^4)(4\times10^{-3})} = 10^{-3}$$



CheckPoint 10





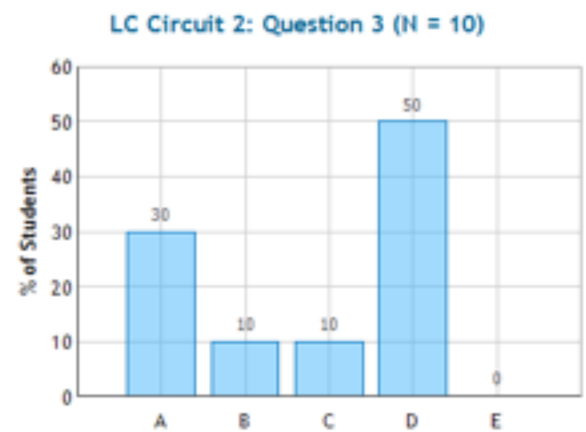
Which plot best represents the energy in the inductor as a function of time starting just after the switch is closed?

$$U_L = \frac{1}{2} L I^2$$

Energy proportional to $I^2 \Rightarrow C$ cannot be negative

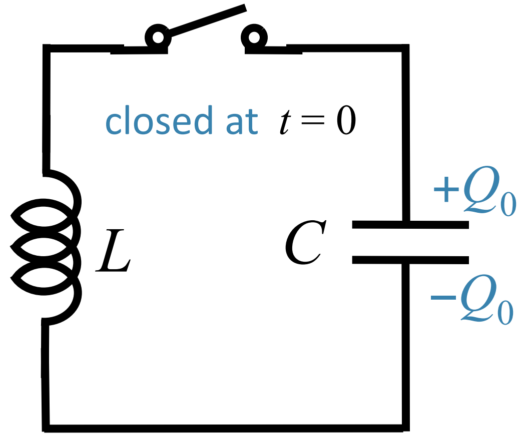
Current is changing $\Rightarrow U_L$ is not constant

Initial current is zero

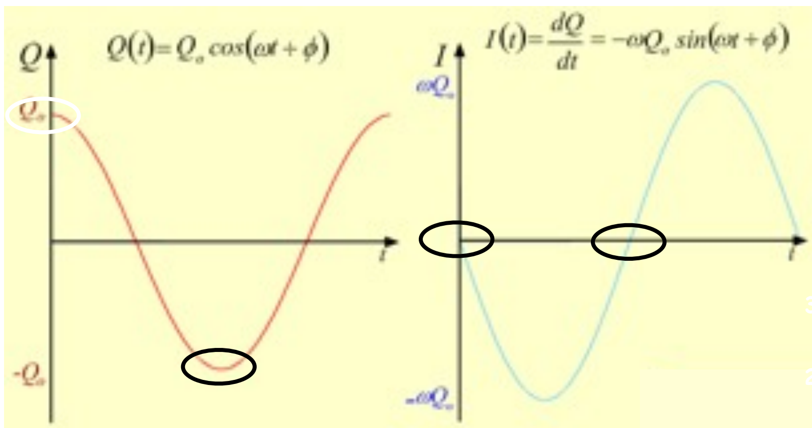


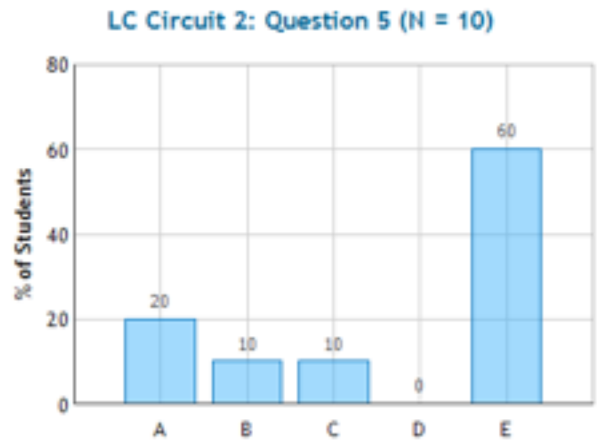
CheckPoint 12

When the energy stored in the capacitor reaches its maximum again for the first time after $t = 0$, how much charge is stored on the top plate of the capacitor?



A) $+Q_0$
B) $+Q_0/2$
C) 0
D) $-Q_0/2$
E) $-Q_0$





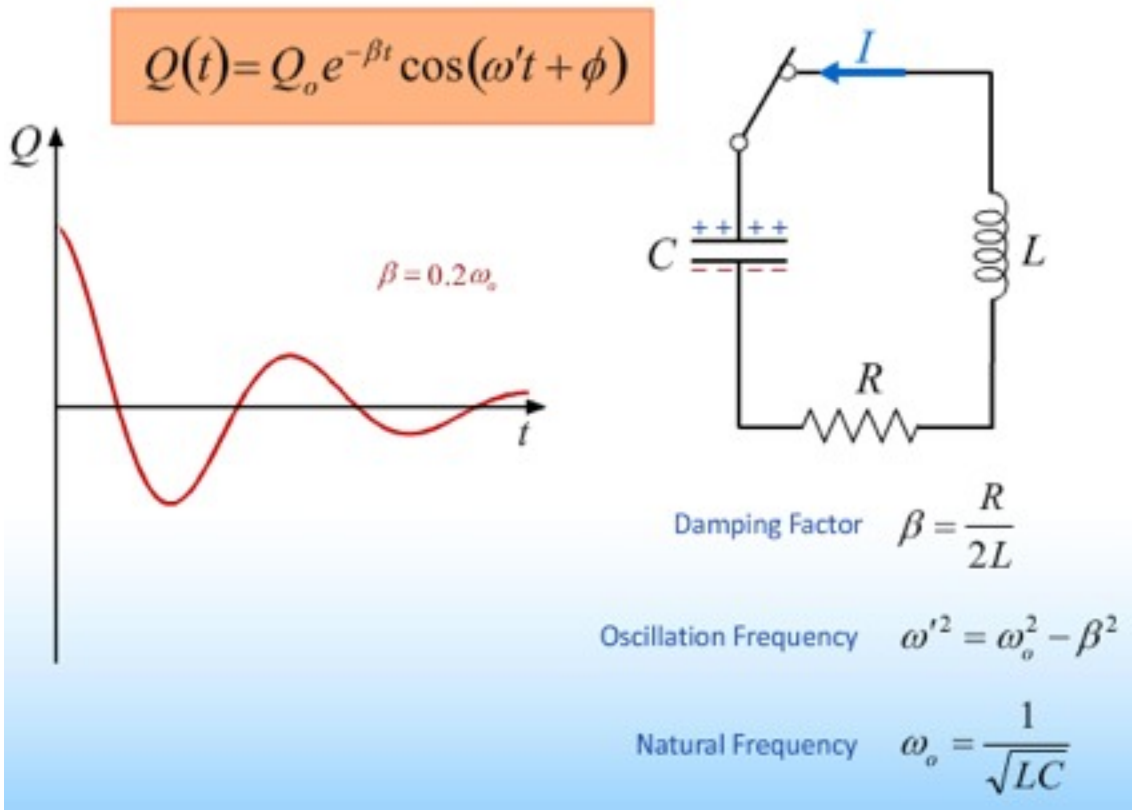
Q is maximum when current goes to zero

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

Current goes to zero twice during one cycle

Add R: Damping

Just like LC circuit but the oscillations get smaller because of R



Concept makes sense… …but answer looks kind of complicated

Physics Truth #1:

Even though the answer sometimes looks complicated…

$$Q(t) = Q_o \cos(\omega t - \phi)$$

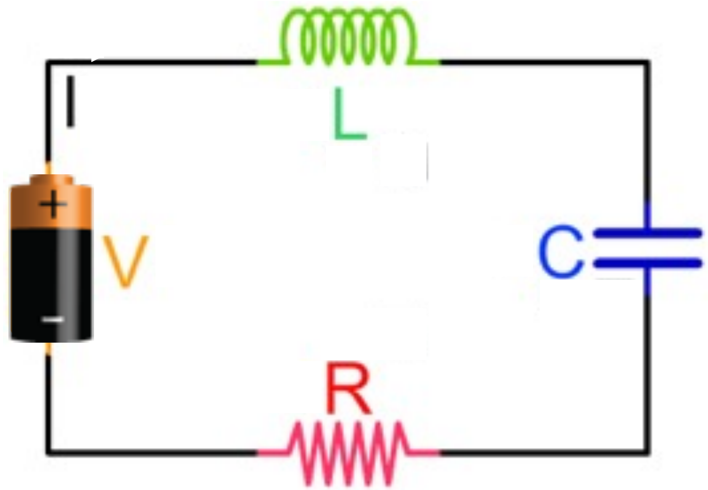
the physics under the hood is still very simple!

$$\frac{d^2Q}{dt^2} = -\omega^2 Q$$

The elements of a circuit are very simple:

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

$$V = V_L + V_C + V_R$$



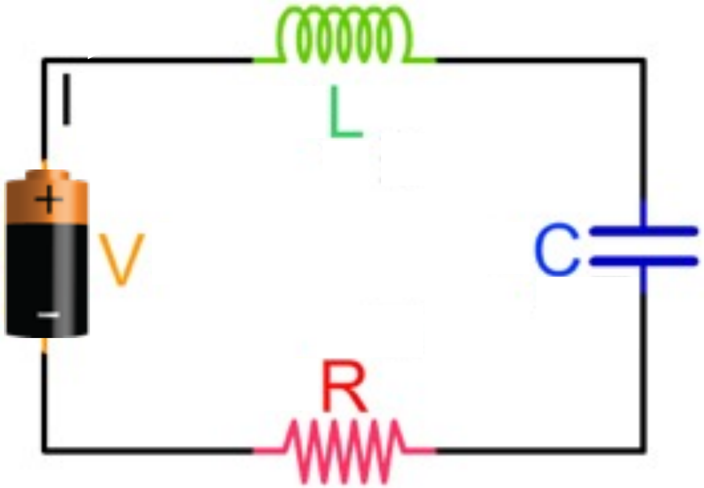
$$V_C = \frac{Q}{C}$$

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

$$V_R = IR$$

This is all we need to know to solve for anything!

A Different Approach



Start with some initial V, I, Q, V_L

Now take a tiny time step dt (1 ms)

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

$$dQ = I dt$$

$$V_C = \frac{Q}{C}$$

$$V_R = IR$$

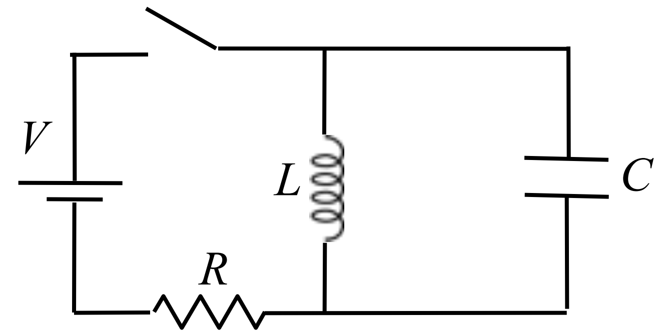
$$V_L = V - V_R - V_C$$

Repeat…

```
for (var t=0; t<tStepSec; t+=dt) {
    I += Vind_last*dt/L;
    Qcap += I*dt;
    Vcap = Qcap/C;
    Vres = I*R1;
    Vind_last = Vind;
    Vind = Va - Vres - Vcap;
}
```

Calculation

The switch in the circuit shown has been closed for a long time. At $t = 0$, the switch is opened.



What is Q_{MAX}, the maximum charge on the capacitor?

Conceptual Analysis

Once switch is opened, we have an LC circuit

Current will oscillate with natural frequency ω_0

Strategic Analysis

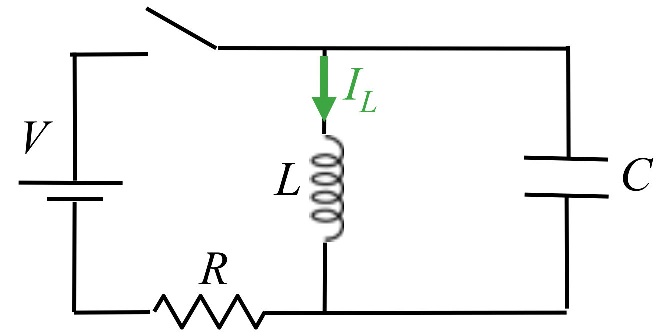
Determine initial current

Determine oscillation frequency ω_0

Find maximum charge on capacitor

Calculation

The switch in the circuit shown has been closed for a long time. At $t = 0$, the switch is opened.



What is I_L, the current in the inductor, immediately after the switch is opened? Take positive direction as shown.

A) $I_L < 0$

B) $I_L = 0$

C) $I_L > 0$

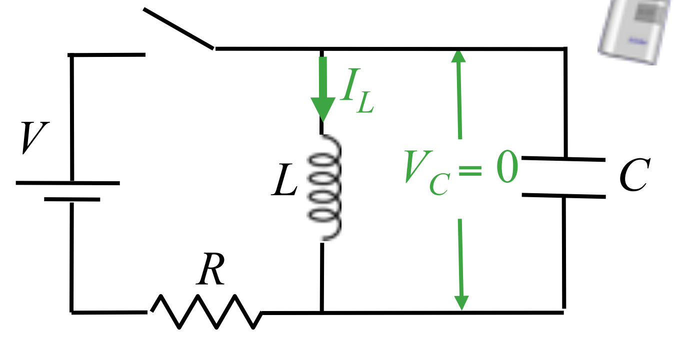
Current through inductor immediately after switch is opened
is the same as
the current through inductor immediately before switch is opened

before switch is opened:

all current goes through inductor in direction shown

Calculation

The switch in the circuit shown has been closed for a long time. At $t = 0$, the switch is opened.



$I_L(t = 0+) > 0$

The energy stored in the capacitor immediately after the switch is opened is zero.

A) TRUE B) FALSE

before switch is opened:

$dI_L/dt \sim 0 \Rightarrow V_L = 0$

BUT: $V_L = V_C$

since they are in parallel

→ $V_C = 0$

after switch is opened:

V_C cannot change abruptly

→ $V_C = 0$

→ $U_C = ½\, C V_C^2 = 0$!

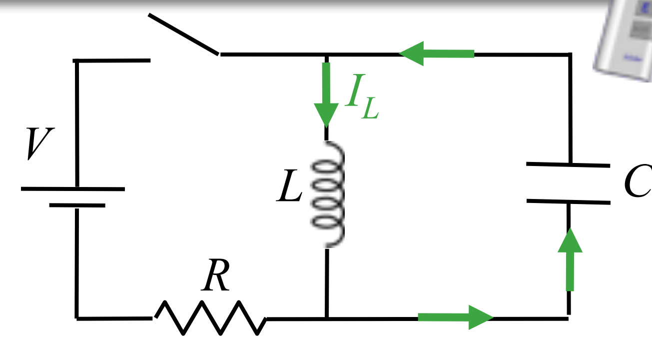
IMPORTANT: NOTE DIFFERENT CONSTRAINTS AFTER SWITCH OPENED

CURRENT through INDUCTOR cannot change abruptly

VOLTAGE across CAPACITOR cannot change abruptly

Calculation

The switch in the circuit shown has been closed for a long time. At $t = 0$, the switch is opened.



$I_L(t = 0+) > 0$ $V_C(t = 0+) = 0$

What is the direction of the current immediately after the switch is opened?

A) clockwise

B) counterclockwise

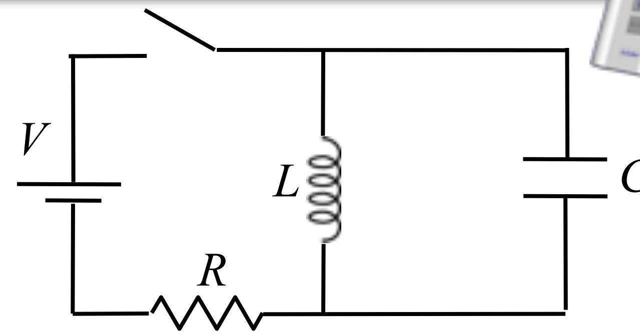
Current through inductor immediately after switch is opened
is the same as
the current through inductor immediately before switch is opened

Before switch is opened: Current moves down through L

After switch is opened: Current continues to move down through L

Calculation

The switch in the circuit shown has been closed for a long time. At $t = 0$, the switch is opened.



$I_L(t = 0+) > 0$ $\quad V_C(t = 0+) = 0$

What is the magnitude of the current right after the switch is opened?

A) $I_o = V\sqrt{\dfrac{C}{L}}$

B) $I_o = \dfrac{V}{R^2}\sqrt{\dfrac{L}{C}}$

C) $I_o = \dfrac{V}{R}$

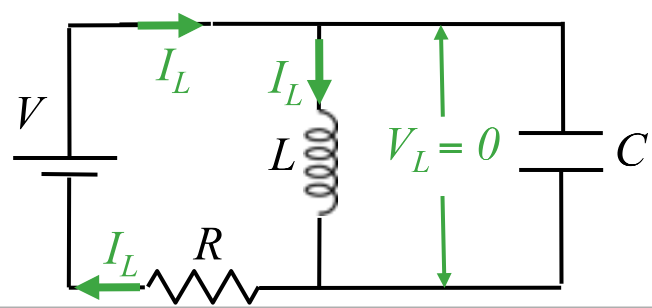
D) $I_o = \dfrac{V}{2R}$

Current through inductor immediately after switch is opened

is the same as

the current through inductor immediately before switch is opened

Before switch is opened:



$V_L = 0$

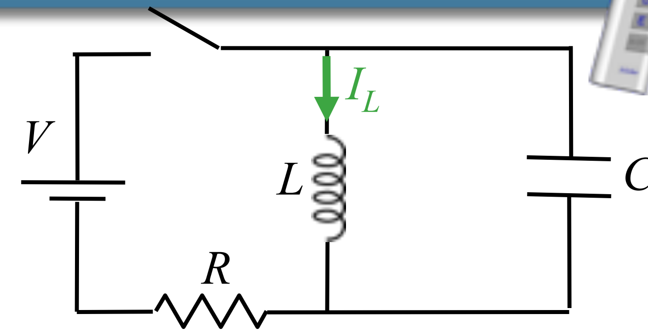
$\downarrow$

$V = I_L R$

Calculation

The switch in the circuit shown has been closed for a long time. At $t = 0$, the switch is opened.

Hint: Energy is conserved



$I_L(t = 0+) = V/R$ $\quad$ $V_C(t = 0+) = 0$

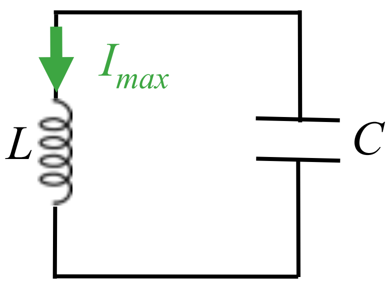
What is Q_{max}, the maximum charge on the capacitor during the oscillations?

A) $Q_{\max} = \frac{V}{R}\sqrt{LC}$

B) $Q_{\max} = \frac{1}{2}CV$

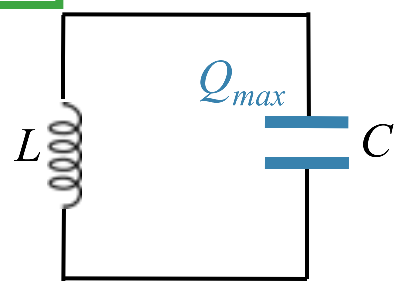
C) $Q_{\max} = CV$

D) $Q_{\max} = \frac{V}{R\sqrt{LC}}$



When I is max (and Q is 0)

$$U = \frac{1}{2}LI^2$$



When Q is max (and I is 0)

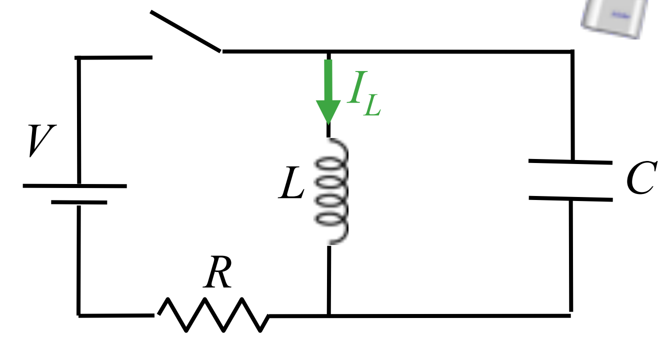
$$U = \frac{1}{2}\frac{Q_{\max}^2}{C}$$

$$\frac{1}{2}LI^2 = \frac{1}{2}\frac{Q_{\max}^2}{C}$$

$$Q_{\max} = I_{\max}\sqrt{LC} = \frac{V}{R}\sqrt{LC}$$

Follow-Up

The switch in the circuit shown has been closed for a long time. At $t = 0$, the switch is opened.



Is it possible for the maximum voltage on the capacitor to be greater than V ?

$I_{max} = V/R$ $\qquad Q_{max} = \frac{V}{R}\sqrt{LC}$

A) YES

B) NO

$$Q_{max} = \frac{V}{R}\sqrt{LC} \rightarrow V_{max} = \frac{V}{R}\sqrt{\frac{L}{C}} \rightarrow$$

V_{max} can be greater than V IF: $\sqrt{\frac{L}{C}} > R$

We can rewrite this condition in terms of the resonant frequency:

$$\omega_0 L > R \quad \text{OR} \quad \frac{1}{\omega_0 C} > R$$

We will see these forms again when we study AC circuits!