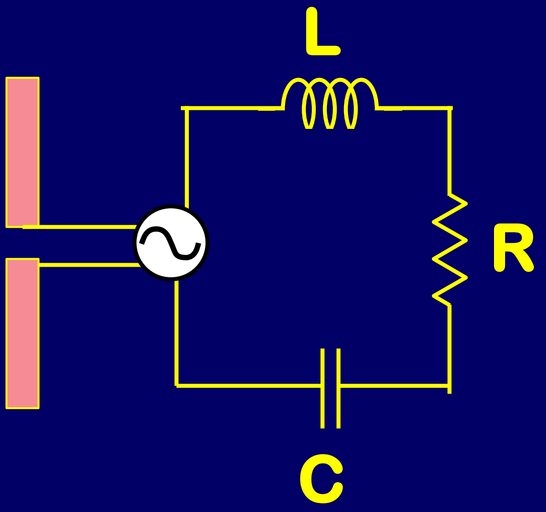
Physics 102: Lecture 13

RLC circuits & Resonance



Ch 21 Prob. 41, 43, 49, 53, 55, 59

Review: AC Circuit

- $I = I_{max}\sin(2\pi ft)$
- $V_R = I_{max}R\sin(2\pi ft)$

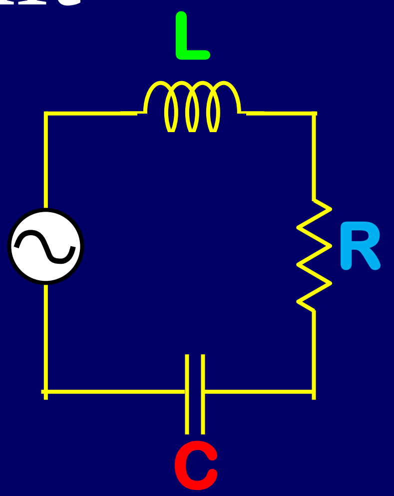
  V_R in phase with I
- $V_C = I_{max}X_C\sin(2\pi ft - \pi/2)$

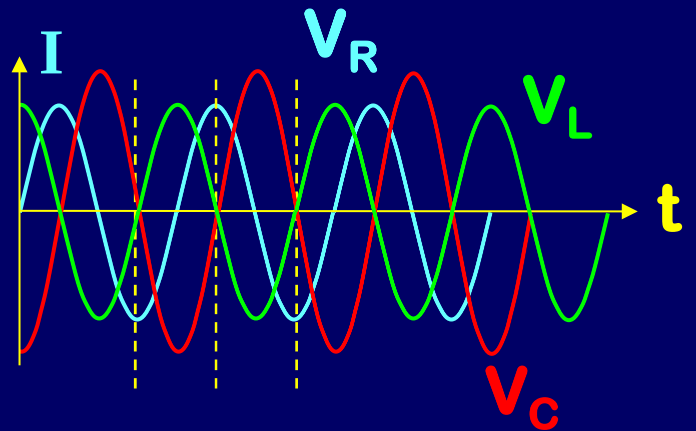
  V_C lags I **"ICE"**

  $V_{C,\max} = I_{\max}X_C \quad X_C = 1/\omega C$
- $V_L = I_{max}X_L\sin(2\pi ft + \pi/2)$

  V_L leads I **"ELI"**

  $V_{L,\max} = I_{\max}X_L \quad X_L = \omega L$



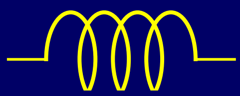


Goal:

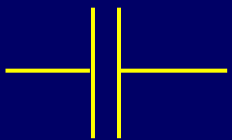
write down equations for all of the voltages

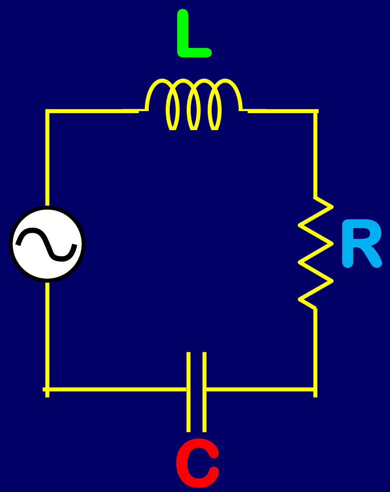
$V_R = I_{max} R \sin(2\pi ft)$

$V_L = I_{max} X_L \sin(2\pi ft + \pi/2)$

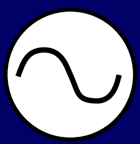


$V_C = I_{max} X_C \sin(2\pi ft - \pi/2)$





The only element left: generator!



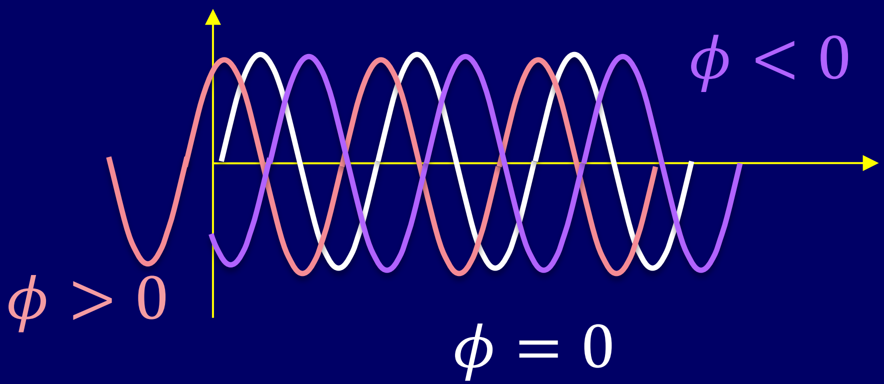
$$V_{gen} = V_{gen,max} \sin(2\pi ft + \phi)$$

ϕ: **"phase angle"**

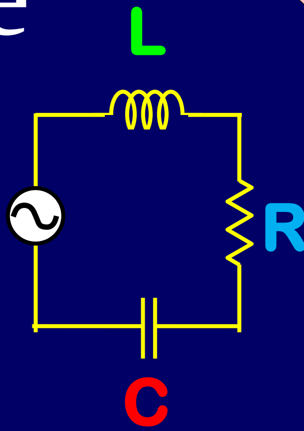
Like a shift in time!

$\phi < 0$: **shift forward**

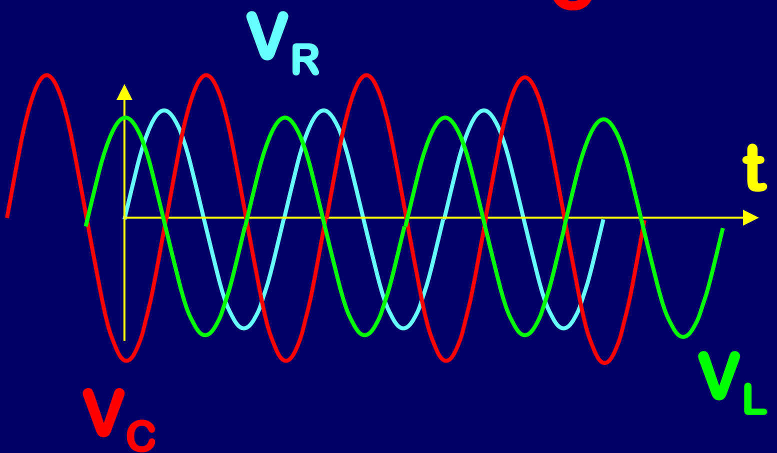
$\phi > 0$: **shift backward**



Kirchhoff: generator voltage



- Instantaneous voltage across generator (V_{gen}) must equal sum of voltage across all of the elements at all times:



$$V_{gen}(t) = V_R(t) + V_C(t) + V_L(t)$$

$$\mathbf{V_{gen,max} \neq V_{L,max} + V_{R,max} + V_{C,max}}$$

What is $V_{gen,max}$?

Define <u>impedance</u> Z: $V_{gen,max} \equiv I_{max} Z$ **Like: V=IR**

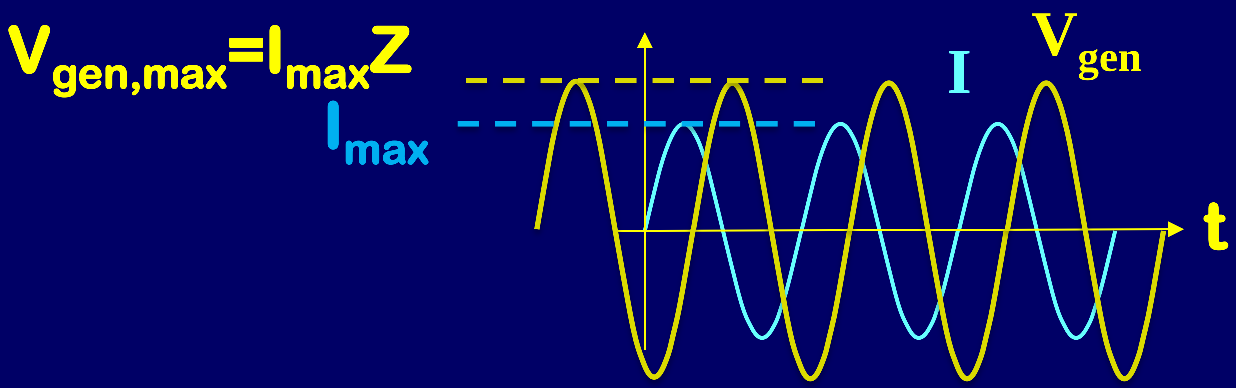
$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

One last ingredient: is the generator voltage leading or lagging the current?

$$I = I_{max}\sin(2\pi ft)$$

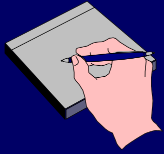
$$V_{gen} = I_{max}Z\sin(2\pi ft + \phi)$$

Phase angle: $\tan(\phi) = \dfrac{(X_L - X_C)}{R}$



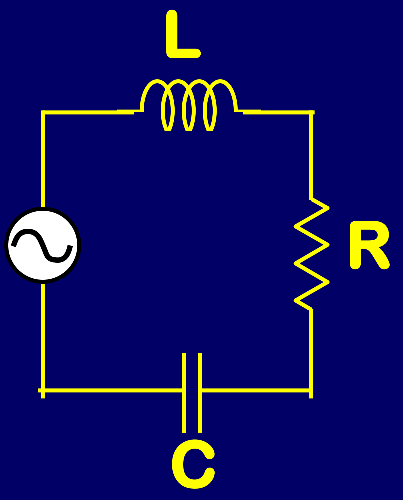
This example: $\phi < 0$, **voltage is lagging**

Example



Problem Time!

An AC circuit with R = 2 Ω, C = 15 mF, and L = 30 mH is driven by a generator with voltage V(t)=2.5 sin(8πt) Volts. Calculate the maximum current in the circuit, and the phase angle.



$$I_{max} = V_{gen,max} / Z$$

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

$$Z = \sqrt{2^2 + \left(8\pi \times .030 - \frac{1}{8\pi \times .015}\right)^2} = 2.76\Omega$$

$$I_{max} = 2.5/2.76 = 0.91 \text{ Amps}$$

$$\tan(\phi) = \frac{X_L - X_C}{R} = \frac{\left(8\pi \times .030 - \frac{1}{8\pi \times .015}\right)}{2} \Rightarrow \varphi = -43.5^\circ$$

Power in RLC circuits

- The voltage generator supplies power.
  - Only resistor dissipates power.
  - Capacitor and Inductor store and release energy.
- $P(t) = I(t)V_R(t)$ oscillates so sometimes power loss is large, sometimes small.
- Average power dissipated by resistor:

$$\overline{P} = \tfrac{1}{2} I_{max} V_{R,max}$$

$$= \tfrac{1}{2} I_{max} V_{gen,max} \cos(\phi)$$

$$= I_{rms} V_{gen,rms} \cos(\phi)$$

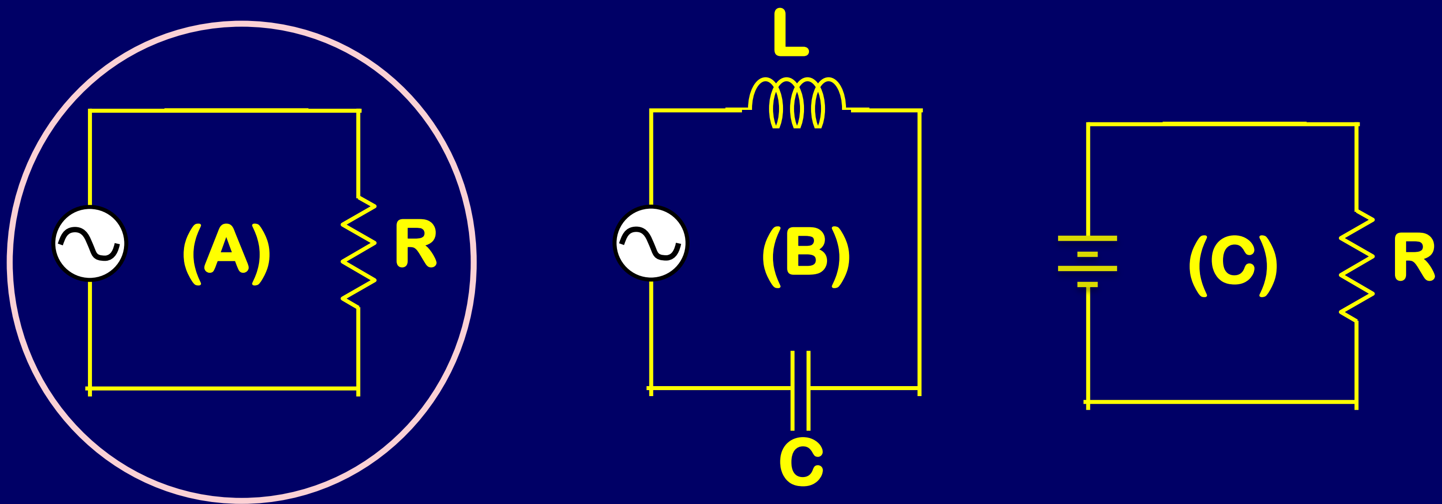
If there is only a resistor, $\phi = 0$

ACT: Power dissipation

Which one of these circuits dissipates the most average power?

The resistance R=2Ω for circuits **A** and **C**, R=0 for **B**

$V_{gen,max} = 10\text{ V}$ $\quad V_{gen,max} = 100\text{ V}$ $\quad \varepsilon = 1\text{ V}$



$P_{avg} = \frac{1}{2} I_{max} V_{gen,max}$

$= \frac{1}{2} V^2_{gen,max}/R$

$= 25\text{ W}$

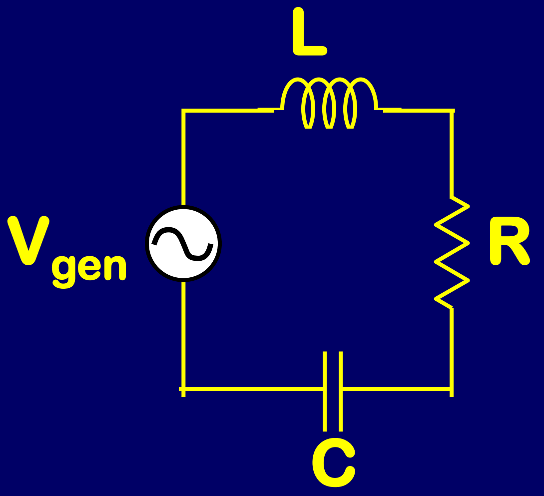
$P_{avg} = 0$

Resistor =0

$P = \varepsilon^2/R$

$= 0.5\text{ W}$

Kirchhoff: generator voltage



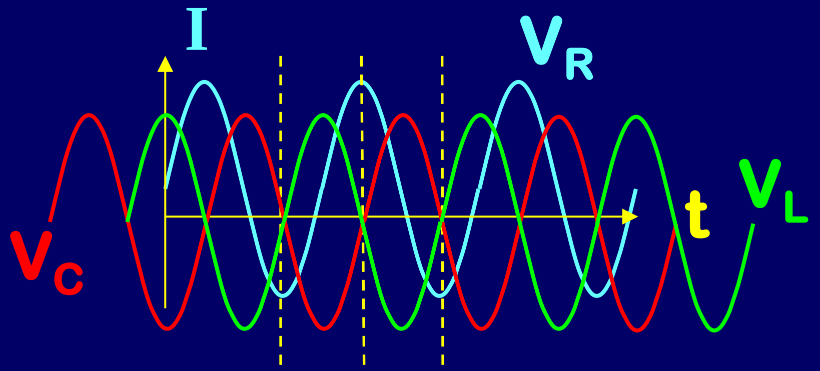
Write down Kirchhoff's Loop Equation:

$V_{gen}(t) = \cancel{V_L(t)} + V_R(t) + \cancel{V_C(t)}$ at every instant of time

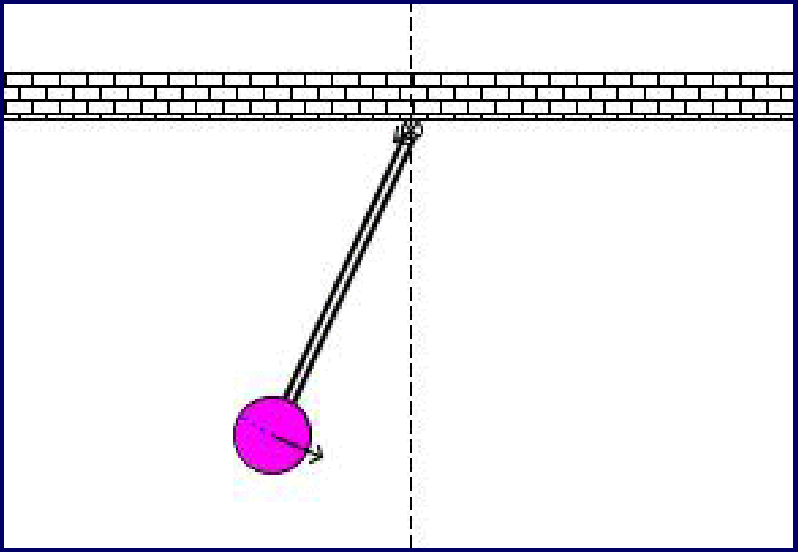
If the frequency is just right...

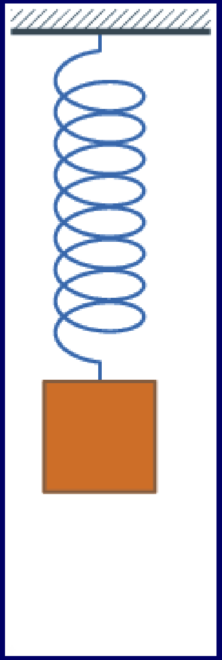
$$V_{gen}(t) = V_R(t)$$

Resonance!



Examples of mechanical resonance





Pendulum:

$$\omega_0 = \sqrt{g/l}$$

Mass on a spring:

$$\omega_0 = \sqrt{k/m}$$

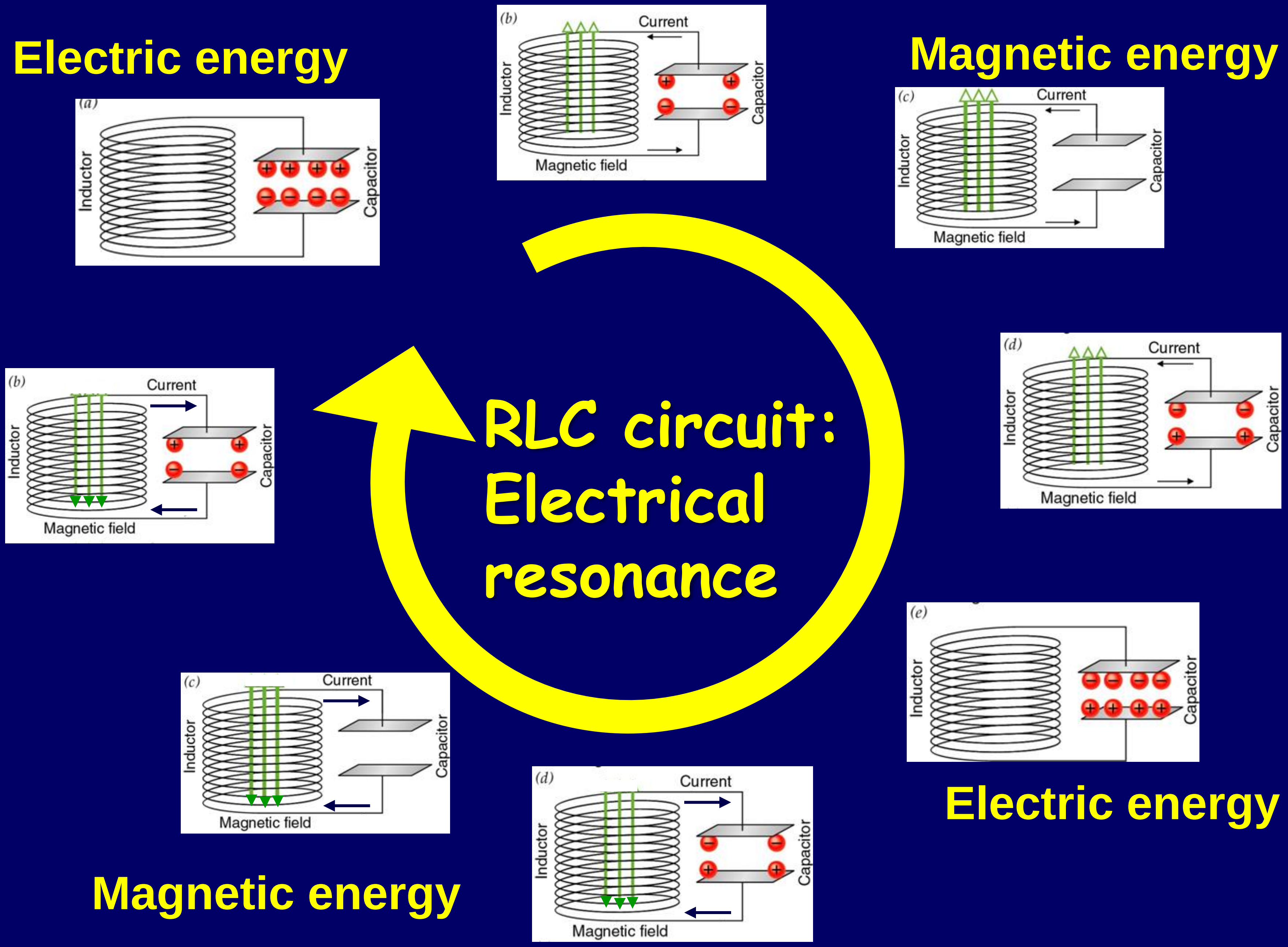
Common features:

- **Energy converts between two forms (kinetic & potential)**
- **Weak input at ω_0 leads to a big response!**

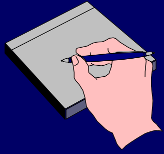
Resonance!

[Tacoma Narrows Bridge]

[Millennium Bridge]


Electric energy
(a)
Inductor
Capacitor
(b)
Current
Inductor
Capacitor
Magnetic field
Magnetic energy
(c)
Current
Inductor
Capacitor
Magnetic field
(b)
Current
Inductor
Capacitor
Magnetic field
RLC circuit:
Electrical
resonance
(d)
Current
Inductor
Capacitor
Magnetic field
(e)
Inductor
Capacitor
Electric energy
(c)
Current
Inductor
Capacitor
Magnetic field
(d)
Current
Inductor
Capacitor
Magnetic field
Magnetic energy

Resonance



R is independent of f

X_L increases with f

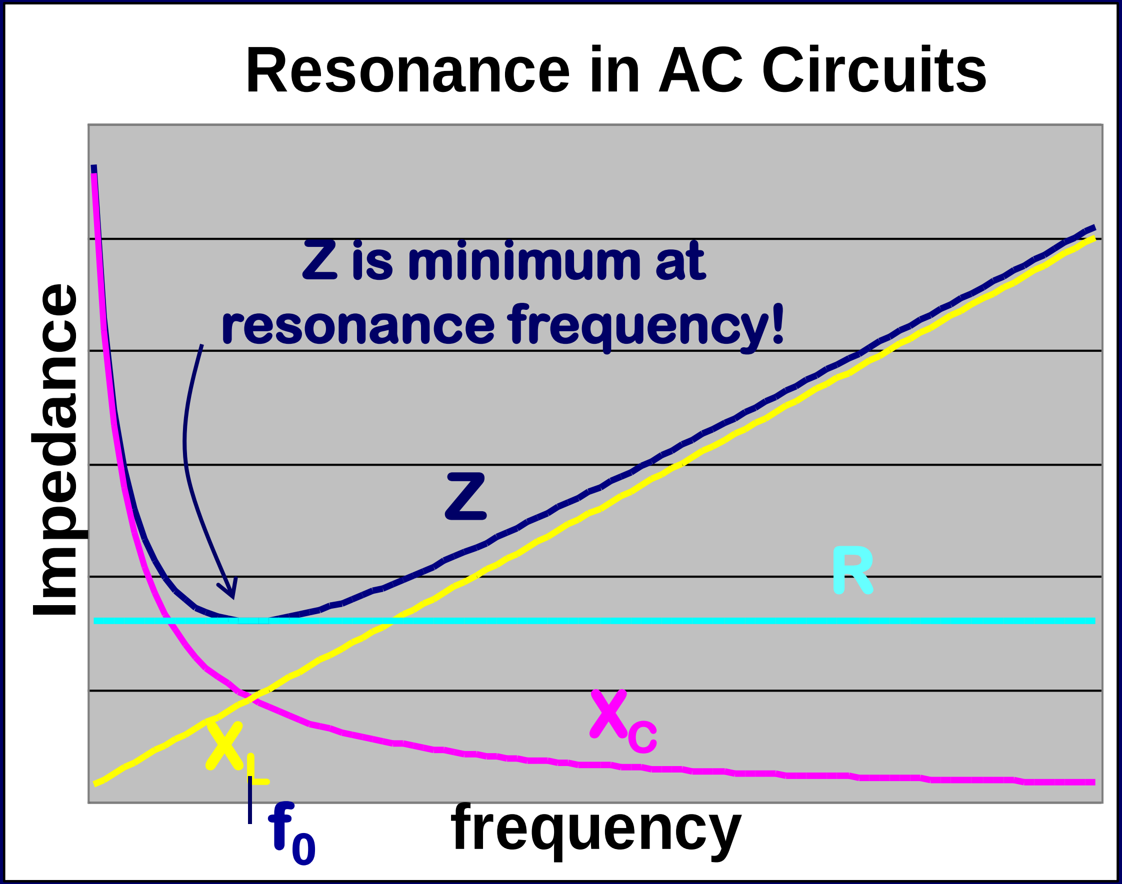
$$X_L = 2\pi f L$$

X_C decreases with f

$$X_C = 1/(2\pi f C)$$

Z: X_L and X_C subtract

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



Resonance: $X_L = X_C$

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

Resonance

R is independent of f

X_L increases with f

$$X_L = 2\pi f L$$

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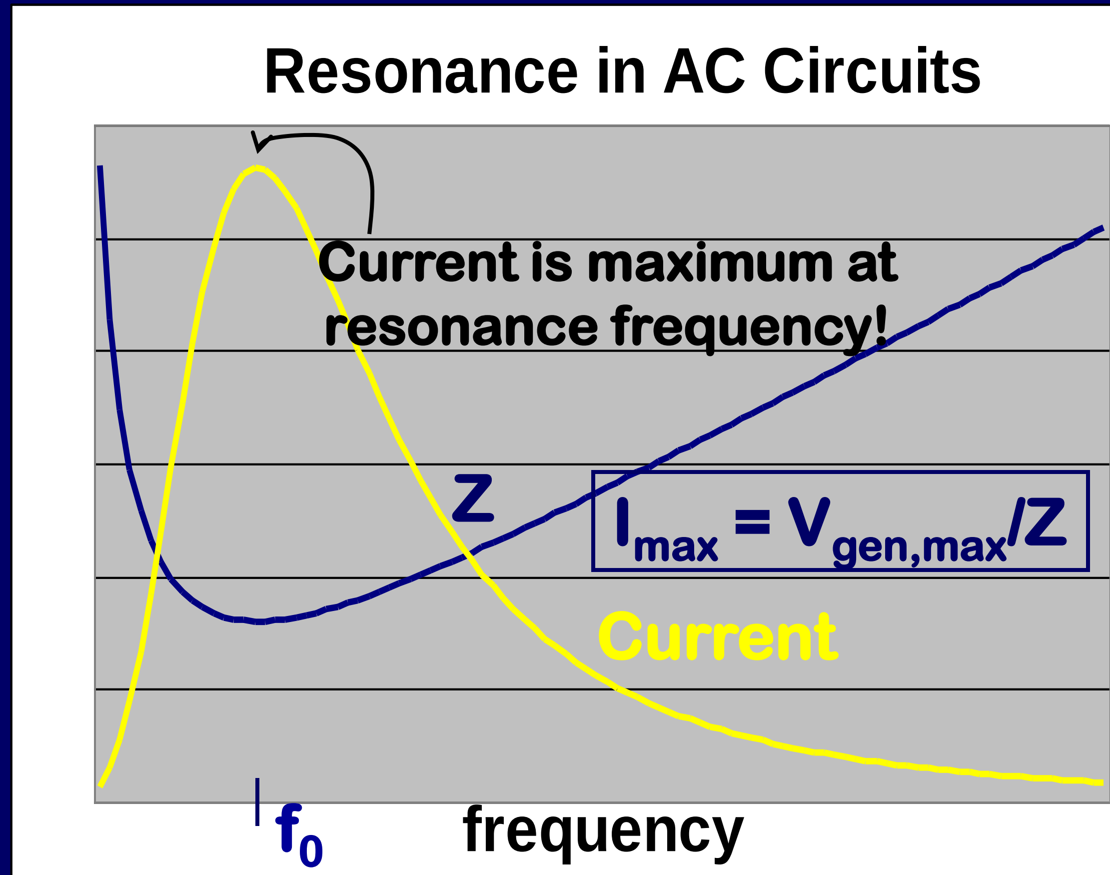
Z: X_L and X_C subtract

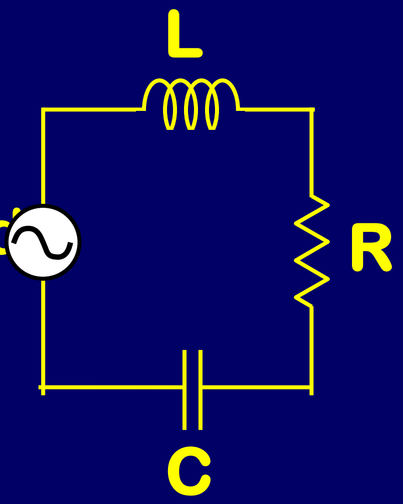
$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$



Resonance: $X_L = X_C$

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \qquad \omega_0 = \frac{1}{\sqrt{LC}}$$

CheckPoint 14.1

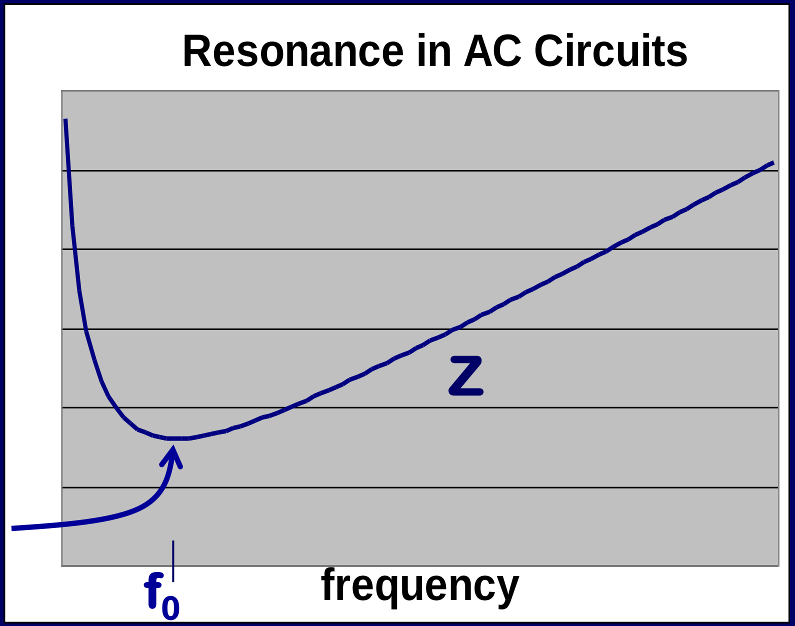


As the frequency of the circuit is either raised above or lowered below the resonant frequency, the impedance of the circuit:

48% Always increases

30% Only increases for lowering the frequency

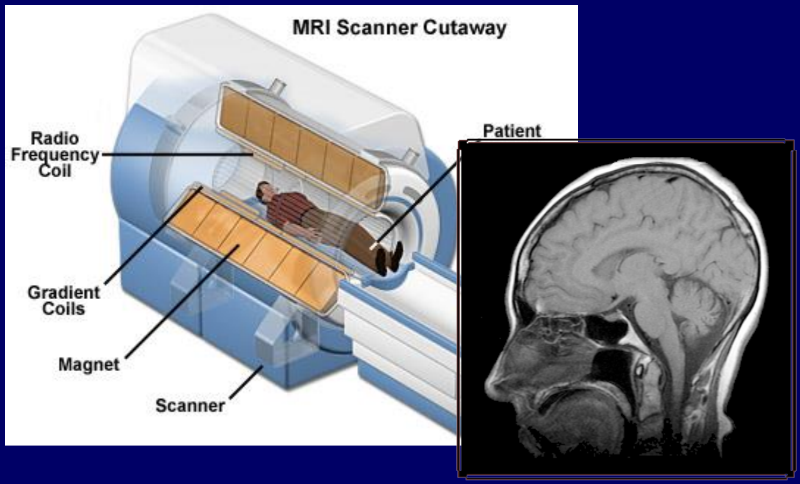
22% Only increases for raising the frequency

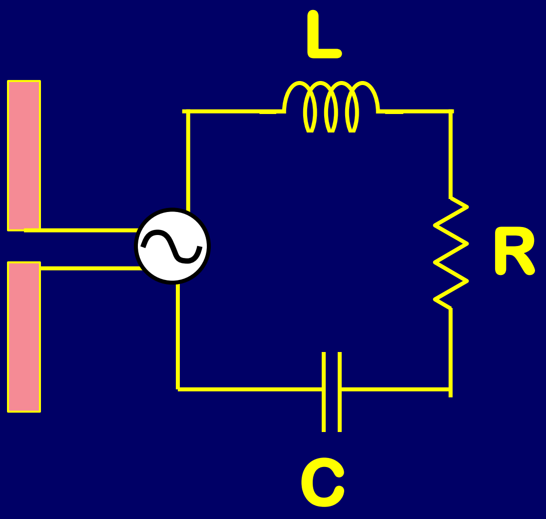


Z is minimum at f_o!

Any other frequency will have higher Z!

What is it good for?





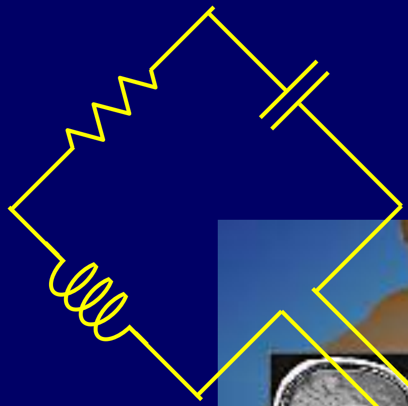
- Current through circuit depends on frequency (maximum at resonance frequency f_o)
  - Radio receiver – Picks out radio station freq f_o
  - NMR/MRI – Picks out signal from protons at f_o

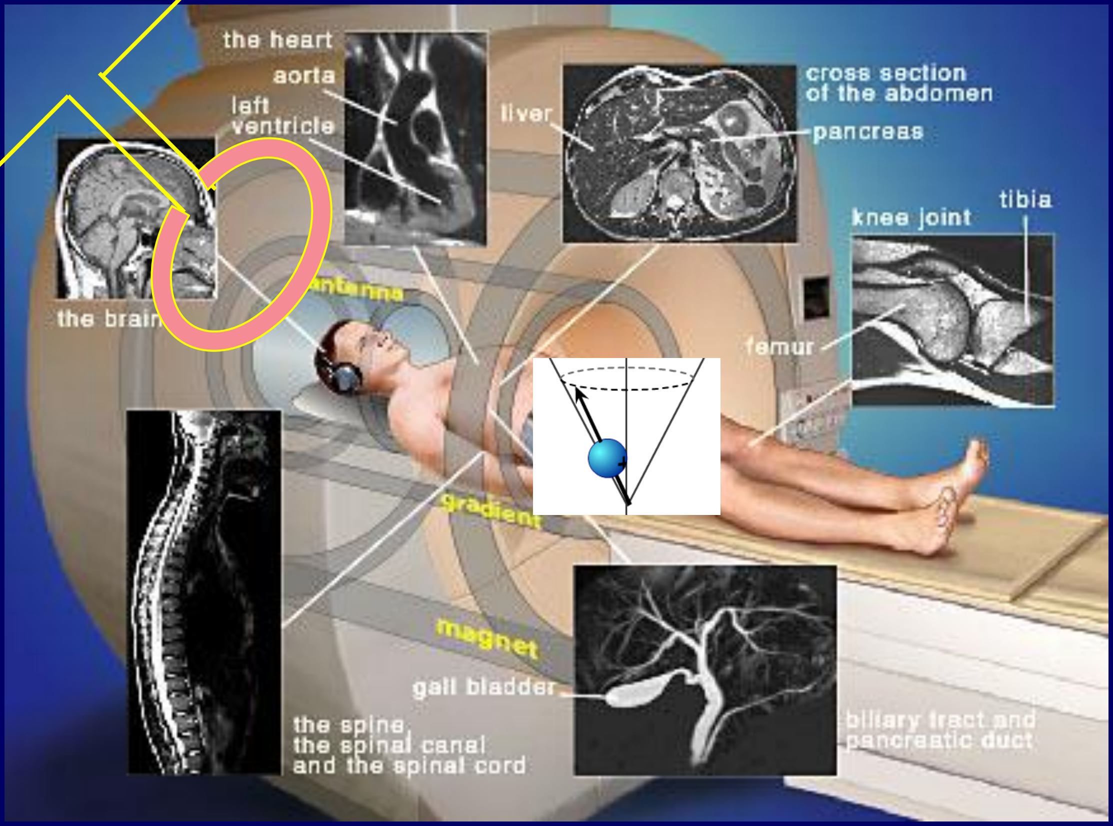
Magnetic Resonance Imaging

Nobel Prize Medicine, 2003

Lauterbur, UIUC

Mansfield



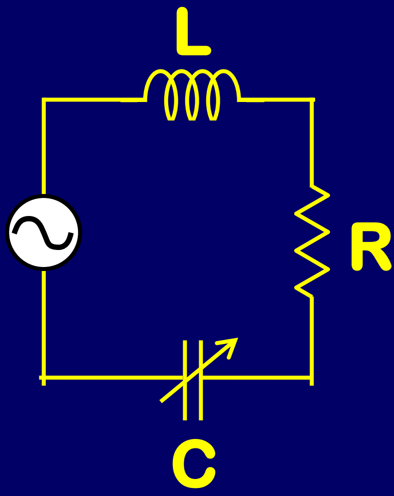


Faraday's Law + RLC circuit!

Example

Resonance in Radios

An AC circuit with R = 2 Ω, L = 0.30 μH and variable capacitance is connected to an antenna to receive radio signals at the resonance frequency. If you want to listen to music broadcasted at 96.1 MHz, what value of C should be used?



$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

$$C = \frac{1}{(2\pi f_0)^2 L} = \frac{1}{\left(2\pi \times 96.1 \times 10^{6}\right)^2 \times 0.30 \times 10^{-6}} = 9.1 \times 10^{-12}\ F$$

ACT: Radios

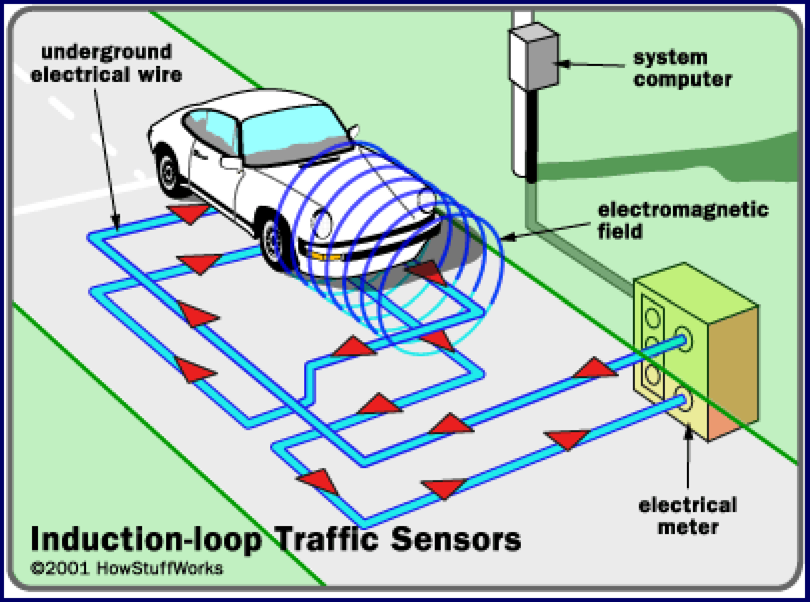
Your radio is tuned to FM 96.1 MHz and want to change it to FM 105.9 MHz, which of the following will work.

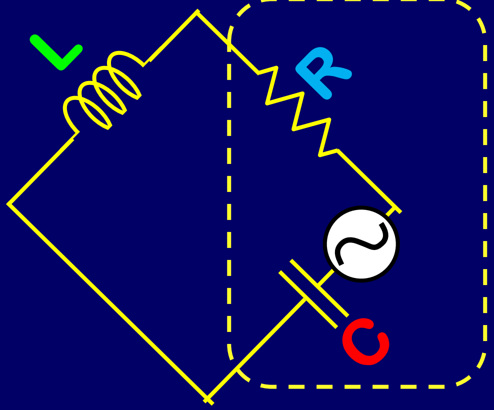
1. Increase Capacitance
2. Decrease Capacitance
3. Neither, you need to change R

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

Higher frequency needs smaller capacitor so it can develop voltage quicker.

Another use for RLC circuits: traffic sensors





AC Summary

Resistors: $V_{R,max} = I_{max} R$

In phase with I

Capacitors: $V_{C,max} = I_{max} X_C$ $X_c = 1/(2\pi f C)$

Lags I

Inductors: $V_{L,max} = I_{max} X_L$ $X_L = 2\pi f L$

Leads I

Generator: $V_{gen,max} = I_{max} Z$ $Z = \sqrt{R^2 + (X_L - X_C)^2}$

Can lead or lag I $\tan(\phi) = (X_L - X_C)/R$

Power is only dissipated in resistor:

$$\bar{P} = \tfrac{1}{2} I_{max} V_{gen,max} \cos(\phi)$$