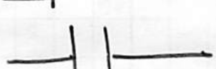
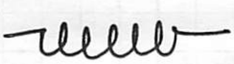
We've studied inductance generally, but now we want see how it might be used more practically. We noticed a few things about self inductance,

$$\phi = LI$$

the emf that is generated when the current changes with time $I = I(t)$, is a back emf, which reflects Lenz's Law. The EMF will be produced to fight the change,

$$\mathcal{E} = -\frac{d\phi}{dt} = -L\frac{dI}{dt}$$

In this equation we can see that the inductance, L, acts like a damping constant on the current, I. We will study the inductors in circuits so let's remind ourselves of the different circuit elements.

Symbol	Circuit Relation	Geometry	Field
	$Q = CV$ or $I = C\,dV/dt$	$C = \frac{\varepsilon_0 A}{d}$ (parallel plates)	$E = \sigma_q/\varepsilon_0$
	$V = IR$	$R = \rho L/A$ (uniform rod)	$J = \sigma E$
	$V = -L\frac{dI}{dt}$	$L = \mu_0 n A * N_{turns}$	$B = \mu_0 n I$ or $\Phi_B = LI$

Kirchoff's Laws say, $\underset{\text{around any closed loop}}{\sum} \Delta V = 0$ and $\underset{\text{all currents entering any node}}{\sum I_{in}} = 0$

"Solving a circuit problem" means finding $I(t)$ &/or $V(t)$ for all circuit elements.

A few more notes before we get into solving problems,

Sources in circuits can be AC or DC, voltage or current sources,

<u>Constant Voltage</u>

Battery
$V = V_0$

<u>Function Generators</u>

AC Voltage Source
$V = V_0 \sin(\omega t + \delta)$

$I \uparrow$

AC current source
$I = I_0 \sin(\omega t + \delta)$

More Notes:

$\varepsilon_0 = 8.85 \cdot 10^{-12} \frac{\text{farad}}{m}$

- real capacitors range from $\underbrace{\lesssim 1pf}_{10^{-12}F}$ to $\underbrace{> 1F}_{\text{serious dielectrics}}$

- Typical resistors range from $< 1\Omega$ to $\underbrace{\text{several } M\Omega}_{\sim 10^6 \Omega}$

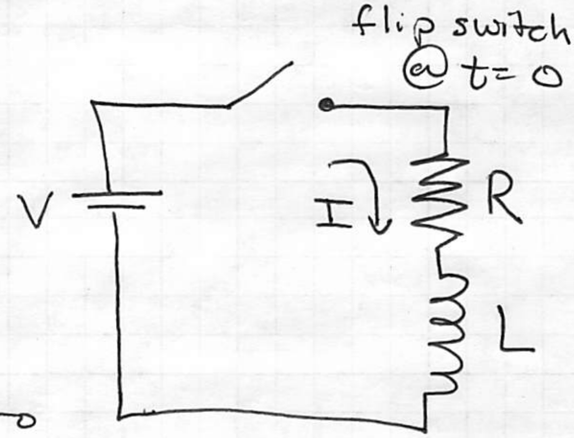
$\mu_0 = 4\pi \cdot 10^{-7} \frac{H}{m}$ (and $L = \frac{\mu_0 N^2 A}{\ell}$) means

- real life inductors range from $< 10^{-6} H$ to ~ 1 Henry

You might be worried about putting an inductor into a circuit and how we define a potential drop across it. This is where ΔV & EMF start to get a little confusing. Both are related to energy &/or work. So what we are saying when we say $\mathcal{E} = -L\, dI/dt$ is that the work per unit charge for this element is $-L\, dI/dt$ so we can use this form in Kirchoff's Law

$$\Sigma \Delta V = 0.$$

Example: the RL circuit.



The resistance might be distributed (in wires, battery, etc). And so might the inductance. This is a model.

This model will allow us to see the general solution method.

Intuitively, the inductor doesn't "like" instant changes in current. We expect that at $t=0$, the current slowly changes from zero. After a <u>long time</u>, there are no more changes. We've reached steady state! $\Delta V_{inductor}=0$, so it acts like an ideal wire now.

Using Kirchoff's Loop Rule we find,

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

Here, we assume that V, R, & L are all known and we are seeking $I(t)$.

This equation is a 1^{st} order, inhomogeneous ODE,

$$L\frac{dI}{dt} + IR = V$$

There are several methods to solve this ODE. We will discuss two

1. Direct method using homogeneous & particular solutions
2. Using the "phasors" method, which is very powerful and can be much simpler.

Method #1 : Direct Solution (maybe remember from ODEs)

① Find the general homogeneous solution to :

$$L\frac{dI_H}{dt} + I_H R = 0$$

② Find some particular solution to the full (inhomog) eq'n.

③ Add these solutions ($I = I_H + I_p$) to get the full solution.

④ Determine the one arbitrary constant in I_H using initial conditions.

this method works for $V = V_0$ (battery)

also if $V = V_0 \cos(\omega t)$ (AC power supply)

and thus, by superposition, we can solve for any periodic $V(t)$ because Fourier says,

$$V(t) = \sum_n V_n \cos(\omega_n t + \delta_n)$$

* this method is fairly general.

Back to the example, the homogeneous equation is,

$$\frac{dI_H}{dt} = -\frac{R}{L} I_H \Rightarrow \text{seperates simply} \Rightarrow \frac{dI_H}{I_H} = -\frac{R}{L}dt$$

$$I_H(t) = I_H(t=0)\, e^{-Rt/L}$$

this is an undetermined constant.

the resistor, R, kills off the current while the inductor, L, stretches that time out.

To find particular solutions, you don't need generality. Any solution that works is the solution. Guess & check is just fine.

Let's say that $V = V_0 = \text{constant}$,

$$L \frac{dI_p}{dt} + I_p R = V_0$$

Given our homogeneous solution maybe something like this works,

$$I_p(t) = a e^{-Rt/L} + b$$ Let's check if this works.

$$\frac{dI_p}{dt} = -\frac{R}{L} a e^{-Rt/L}$$ so that,

$$L\left(-\frac{R}{L} a e^{-Rt/L}\right) + \left(a e^{-Rt/L} + b\right) R = V_0$$

the exponential terms cancel! this leaves

$bR = V_0$ so our proposed solution works if

$b = V_0/R$

Add the solutions together,

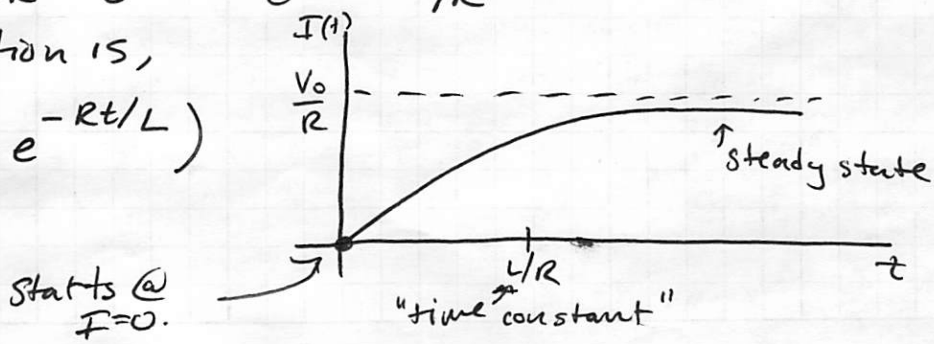
$$I(t) = I_p + I_H = \underbrace{\left(I_H(t=0) + a\right)}_{\text{call this a constant, } c} e^{-Rt/L} + V_0/R$$

$$I(t) = Ce^{-Rt/L} + V_0/R$$ if at $t=0$, $I=0$ then,

$$I(0) = C + V_0/R = 0 \qquad C = -V_0/R$$

so our solution is,

$$I(t) = \frac{V_0}{R}\left(1 - e^{-Rt/L}\right)$$



We will observe more interesting results when we have an AC supply. Let's work on this for,

$V(t) = V_0 \cos(\omega t)$

We have already found the homogeneous solution, I_H, so we just need a good guess for $I_p(t)$.

We'd expect that a sinusoidal source would result in a sinusoidal solution, so let's try,

$I_p(t) = a\cos(\omega t + \varphi)$

these are both undetermined coefficients.

Our differential equation is now,

$L\, dI_p/dt + I_p R = V_0 \cos(\omega t)$

$-La\omega \sin(\omega t + \varphi) + aR\cos(\omega t + \varphi) = V_0\cos(\omega t)$

this looks a little complex but we can simplify things with standard trig identities,

$\sin(a+b) = \sin a \cos b + \cos a \sin b$

$\cos(a+b) = \cos a \cos b - \sin a \sin b$

If we use these identities we find,

$$\begin{matrix} -La\omega \sin\omega t \cos\varphi - aR\sin\omega t \sin\varphi \\ -La\omega \cos\omega t \sin\varphi + aR\cos\omega t\cos\varphi \end{matrix} = \begin{matrix} 0 \\ + \\ V_0\cos\omega t \end{matrix}$$

if the coeffs in front of the $\sin\omega t$ terms vanish and those in front of the $\cos\omega t$ terms give V_0, it works!

$$\left.\begin{aligned} -La\omega\cos\varphi - aR\sin\varphi &= 0 \\ -La\omega\sin\varphi + aR\cos\varphi &= V_0 \end{aligned}\right\}$$ Two eqn's and two unknowns (a & φ)

$\Rightarrow$ the first equation we have gives

$$-La\omega\cos\varphi = aR\sin\varphi$$

- if $a=0$, this works, but that means $I_p(t)=0$
- if instead,

$$\tan\varphi = \frac{-L\omega}{R} \quad \text{or} \quad \boxed{\varphi = \tan^{-1}\left(-\frac{L\omega}{R}\right)}$$

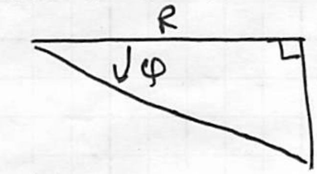
then we get a nonzero I_p.

So φ is not an arbitrary constant and is not dependent on initial conditions. It is determined by the circuit elements and the driver.

$\Rightarrow$ the second equation we have gives,

$$a(-L\omega\sin\varphi + R\cos\varphi) = V_0$$

We can use a triangle that shows $\tan\varphi = \frac{-L\omega}{R}$,



We can read off $\sin\varphi$ & $\cos\varphi$,

$$\sin\varphi = \frac{-L\omega}{\sqrt{R^2+L^2\omega^2}} \qquad \cos\varphi = \frac{+R}{\sqrt{R^2+L^2\omega^2}}$$

Let's put these back into the 2nd equation,

$$a\left(\frac{L^2\omega^2}{\sqrt{R^2+L^2\omega^2}} + \frac{R^2}{\sqrt{R^2+L^2\omega^2}}\right) = a\left(\sqrt{R^2+L^2\omega^2}\right) = V_0$$

$$\boxed{a = \frac{V_0}{\sqrt{R^2+L^2\omega^2}}}$$

So with $\varphi = \tan^{-1}\left(-\frac{L\omega}{R}\right)$ and $a = \frac{V_0}{\sqrt{R^2+L^2\omega^2}}$,

$$I_p(t) = a\cos(\omega t + \varphi) \text{ works.}$$

So our full solution is,

$$I(t) = I_p + I_H = a\cos(\omega t+\varphi) + I_{H0}\, e^{-Rt/L}$$

= persistent oscillatory response + dying away piece

$\Rightarrow$ a and φ are determined already (on previous page)

I_{H0} is not determined; it is determined by initial conditions.

So if, for example, at $t=0$, $I=0$ then,

$$I(t>0) = a\cos(\omega t+\varphi) - \underbrace{a\cos\varphi}_{\text{makes } I(t=0)=0}\, e^{-Rt/L}$$

with amplitude $a = \dfrac{V_0}{\sqrt{R^2+L^2\omega^2}}$ and phase, $\varphi = \tan^{-1}\left(-\dfrac{L\omega}{R}\right)$

- when R is large, a is small. Big R kills off long term currents.
- when $\omega=0$ (battery), $a \to V_0/R$ and $\tan^{-1}(0) = 0 = \varphi$.
  the inductor acts like an ideal wire in the long term limit w/ DC voltage.
- when $\omega \to \infty$, $a \to 0$; Inductors don't like rapid changes (big Back EMFs!)
  they will suppress response at high f.

This method works just fine, but it's a real pain when you have a more complex circuit. especially w/ multiple R's, L's, & C's in series and/or parallel.

Method 2 Phasors

- The phasor method is a bit more sophisticated, but it's incredibly powerful and widely used.
- It gets rid of the sines & cosines and changes our problem to a simple algebra problem using exponentials.
- We will make use of Euler's famous formula,

$$e^{i\theta} = \cos\theta + i\sin\theta \quad \text{or for our purposes,}$$

$$e^{i\omega t} = \cos\omega t + i\sin\omega t.$$

What's nice about the exponential form is how they work under derivatives (and integrals),

$\frac{d}{dt}(\cos\omega t) = -\omega\sin\omega t$ is a new, linearly ind. function (leads to complications.)

But,

$\frac{d}{dt}(e^{i\omega t}) = i\omega e^{i\omega t}$, just proportional to the original function, $\frac{df}{dt} \propto f$. (much easier!)

So here's what we are going to do. Instead of $V_0\cos\omega t$ as the driver, we will use $V_0 e^{i\omega t}$. Now, this might bother you b/c the voltage is complex. That's fine, at the end of the day we will take the Real Part.

$$V_{true} = Re\left[V_{fictious}\right] \quad \text{and} \quad I_{true} = Re\left[I_{fictious}\right]$$

We can do this b/c the ODE is linear, so $Re(I)$ aries from $Re(V)$. The ODE will be simpler, but we will to remember to take the real part.

Lets rework the problem again using the phasor method,

$$L\frac{dI}{dt} + IR = V(t) = \tilde{V}e^{i\omega t}$$

so we have this (fictious) driving voltage, $\tilde{V}e^{i\omega t}$! It's complex

- the real voltage is $Re(\tilde{V}e^{i\omega t})$
- if $\tilde{V}$ is itself a complex constant (i.e., $\tilde{V} = V_0 e^{i\delta}$), then we can have more complex drivers $V_0\cos(\omega t + \delta)$

We know the solution for I_H, so we just need to find I_p. We will guess & check. This time we guess a simple form: $I_p = \tilde{I}e^{i\omega t}$

$$L\frac{dI_p}{dt} + I_p R = \tilde{V}e^{i\omega t} \quad \text{is the ODE,}$$

$$L\tilde{I}(i\omega)e^{i\omega t} + \tilde{I}Re^{i\omega t} = \tilde{V}e^{i\omega t} \quad \text{the } e^{i\omega t}\text{'s cancel out!}$$

$$L\tilde{I}(i\omega) + \tilde{I}R = \tilde{V} \quad \text{or} \quad \tilde{I} = \frac{\tilde{V}}{R + i\omega L}$$

that's it! $\tilde{I}$ is a constant and our solution is simply,

$$I_{true} = Re(I_{fictous}) = Re(\tilde{I}e^{i\omega t}) + I_H$$

from before

see how much simpler that is!

The solution looks like $\tilde{V} = \tilde{I}\tilde{R}$ with $\tilde{R}$ now complex

$\tilde{R}$ is the impedance (or complex impedance), we label it Z

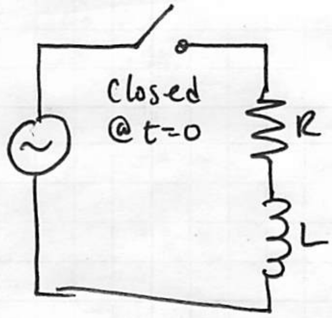
for  we got $Z = R + i\omega L$ $\Big\}$ a series circuit just add the impedances $\Big\}$ more general actually!

$Z_R = R$ resistor

$Z_L = i\omega L$ inductor

(turns out a capacitor has $Z_C = \frac{-i}{\omega C}$)

Let's return to the RL example and wrap it up,



$$Z_{tot} = R + i\omega L$$

so we have, $\tilde{V} = \tilde{I}(R + i\omega L)$

and $V_{true} = \mathrm{Re}\, \tilde{V} e^{i\omega t}$

$$I_{true} = \mathrm{Re}\, \tilde{I} e^{i\omega t} = \mathrm{Re}\left(\frac{\tilde{V} e^{i\omega t}}{R + i\omega L}\right)$$

In our original setup, $V_{real} = V_0 \cos \omega t$ so $\tilde{V} = V_0$

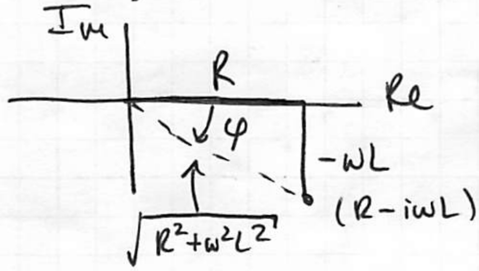
So we have:

$$I_{true} = \mathrm{Re}\left(\frac{V_0 e^{i\omega t}}{R + i\omega L}\right) = \mathrm{Re}\left(\frac{V_0 e^{i\omega t}}{R + i\omega L} \frac{R - i\omega L}{R - i\omega L}\right)$$

Standard method

so, $$I = \frac{V_0}{R^2 + \omega^2 L^2} \mathrm{Re}\left(e^{i\omega t}(R - i\omega L)\right)$$

How do we deal with the rest of the expression? Another standard method, draw $R - i\omega L$ in the complex plane,



In the complex plane, this point is simply,

$$\sqrt{R^2 + \omega^2 L^2}\, e^{i\phi} \quad \text{with } \varphi = \tan^{-1}\left(\frac{-\omega L}{R}\right)$$ as before

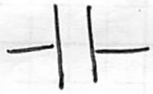
so, $$I = \frac{V_0}{\sqrt{R^2 + \omega^2 L^2}} \mathrm{Re}\left(e^{i\omega t} e^{i\phi}\right) = \frac{V_0}{\sqrt{R^2 + \omega^2 L^2}} \cos(\omega t + \varphi)$$

this is the exact solution we had before but now $V = IZ$

this works for $V = V_0 \cos(\omega t + \delta) \Rightarrow$ use $\tilde{V} = V_0 e^{i\delta}$

or for $V = V_0 \sin(\omega t) \Rightarrow$ use $\tilde{V} = V_0 e^{i\pi/2}$

What if there's a capacitor? Can we use the same tools?



$$V = \frac{Q}{C} \Rightarrow \frac{dV}{dt} = \frac{I}{C} \quad \text{or that } I = C\frac{dV}{dt}$$

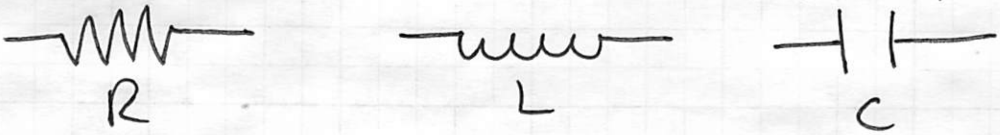
So if the driver is $V(t) = \tilde{V}e^{i\omega t}$ then,

$$I = Ci\omega\tilde{V}e^{i\omega t} = i\omega C V$$

This looks like $V = I$"R" but this time the impedance is $Z_c = \frac{1}{i\omega C} = \frac{-i}{\omega C}$ (we use Z to indicate complex impedance)

<u>Summary</u>

$Z = R$ $\qquad$ $Z = i\omega L$ $\qquad$ $Z = -i/\omega C$



General Result: you can treat each passive element like a simple resistor with the impedances given above. You can construct Z_{eff} using the standard "rules" for resistors.

In series,

$$Z_{eff} = Z_1 + Z_2 + Z_3 + \dots$$

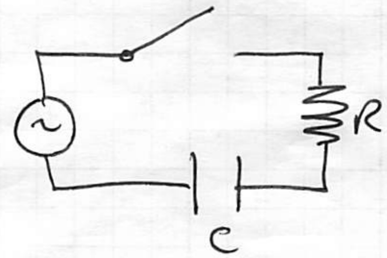
In parallel,

$$\frac{1}{Z_{eff}} = \frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_3} + \dots$$

Can apply usual Kirchoff's Laws to them as well.

Example! An RC Circuit

Turn it on @ $t=0$
with $V(t) = V_0 \cos\omega t$



think of this as two Z's,

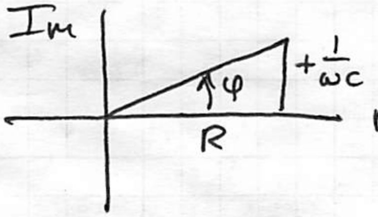
$$Z_{tot} = Z_R + Z_C = R - i/\omega C$$

with, $\tilde{V} = \tilde{I} Z \Rightarrow \tilde{I} = \dfrac{\tilde{V}}{R - i/\omega C}$ and $I_{real} = V_0 \, \mathrm{Re}\left(\dfrac{e^{i\omega t}}{R - i/\omega C}\right)$

the first part uses this method again,

$$I = V_0 \, \mathrm{Re}\left(\frac{e^{i\omega t}}{R - i/\omega C} \; \frac{R + i/\omega C}{R + i/\omega C}\right) = \frac{V_0}{R^2 + \frac{1}{\omega^2 C^2}} \mathrm{Re}\left(e^{i\omega t}\left(R + \frac{i}{\omega C}\right)\right)$$

Use the second method, draw a picture,



$$\varphi = \tan^{-1}\left(\frac{1}{\omega C R}\right)$$

and $e^{i\varphi} = \dfrac{R}{\sqrt{R^2 + \frac{1}{\omega^2 C^2}}} + \dfrac{i/\omega C}{\sqrt{R^2 + \frac{1}{\omega^2 C^2}}}$

So the particular solution is,

$$I_p = \frac{V_0}{\sqrt{R^2 + 1/\omega^2 C^2}} \cos(\omega t + \varphi)$$

We still need to solve the homogeneous equation,

$$0 = IR + Q/C \Rightarrow \frac{dI}{dt} R = -\frac{I}{C}$$

take time derivative
$(dQ/dt = I)$

So, $\dfrac{dI}{I} = -\dfrac{1}{RC} dt \Rightarrow I_H = I_0 e^{-t/RC}$

So

$$I_{tot} = \underbrace{\frac{V_0}{\sqrt{R^2 + 1/\omega^2 C^2}} \cos(\omega t + \varphi)}_{\text{steady solution}} + I_0 \underbrace{e^{-t/RC}}_{\text{transient dies off}}$$

I_0: TBD by initial conditions.

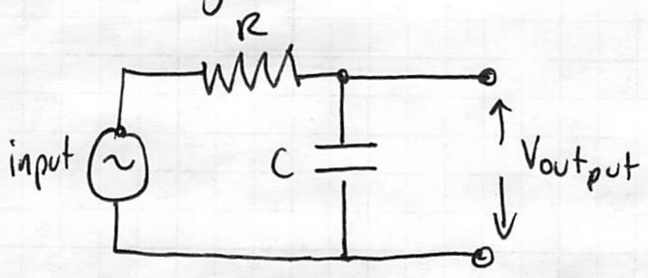
Initial Conditions: ΔV_{cap} cannot suddenly change.
If it was zero before then just after $V_0 = IR$ b/c $\Delta V_{cap} = 0$ for just a quick moment. So $I(t=0) = V_0/R$.

So, this gives,

$$I(t) = \frac{V_0}{\sqrt{R^2 + 1/\omega^2 C^2}} \cos(\omega t + \varphi) + \underbrace{\left(\frac{V_0}{R} - \frac{V_0 \cos\varphi}{\sqrt{R^2 + 1/\omega^2 C^2}} \right)}_{\text{picked so @ } t=0 \ I = V_0/R} e^{-t/RC}$$

- time constant is "RC"
- After waiting several RC times the circuit oscillates with driver frequency, ω
- If $\omega \to 0$, $I_{\text{long term}} \to 0$, the capacitor blocks steady current.
- if $\omega \to \infty$, $I_{\text{long term}} \to \frac{V_0}{R}\cos(\omega t)$ like the capacitor isn't there.

It's often useful to put this setup in a circuit where you can read out a voltage (as a signal)



We know I in this circuit and V_{out} is,

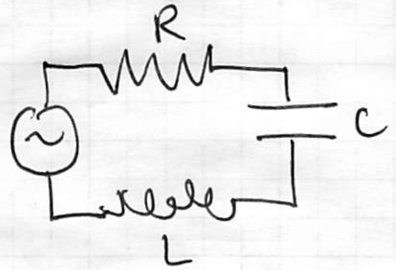
$$V_{out} = I Z_C = I(-i/\omega C)$$

$$V_{out} = \frac{V_{in}}{Z_{tot}} Z_C = \frac{V_{in}}{R - \frac{i}{\omega C}} \left(-i/\omega C\right) = V_{in}\left(\frac{1}{1 + i\omega RC}\right)$$

with $\omega \to 0$, $V_{out} = V_{in}$, cap does nothing

with $\omega \to \infty$, $V_{out} \to 0$, "low pass filter"
Allows low frequencies to pass; suppresses high frequency.

with the phasor method & impedance, any circuit is basically a 184 circuit.



just use $Z = R + i\omega L - \frac{i}{\omega C}$

and then $\tilde{V} = \tilde{I}\tilde{Z}$