Introduction to Electronics

The Prefixes Used with SI Units

Prefix	Symbol	Meaning	Scientific Notation
exa-	E	1,000,000,000,000,000,000	10^{18}
peta-	P	1,000,000,000,000,000	10^{15}
tera-	T	1,000,000,000,000	10^{12}
giga-	G	1,000,000,000	10^{9}
mega-	M	1,000,000	10^{6}
kilo-	k	1,000	10^{3}
hecto-	h	100	10^{2}
deka-	da	10	10^{1}
—	—	1	10^{0}
deci-	d	0.1	10^{-1}
centi-	c	0.01	10^{-2}
milli-	m	0.001	10^{-3}
micro-	μ	0.000 001	10^{-6}
nano-	n	0.000 000 001	10^{-9}
pico-	p	0.000 000 000 001	10^{-12}
femto-	f	0.000 000 000 000 001	10^{-15}
atto-	a	0.000 000 000 000 000 001	10^{-18}

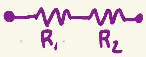
Basic Circuit Analysis

▷ KIRCHHOFF'S LAWS

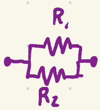
- Loop rule: The sum of ΔV across all elements in a loop is 0.
- Junction rule: The sum of current entering a junction equals current exiting.

Note: ΔV_{AB} means $V_A - V_B$

▷ EQUIVALENT RESISTANCE



$R_{eq} = R_1 + R_2$



$R_{eq} = \dfrac{1}{\frac{1}{R_1} + \frac{1}{R_2}}$

▷ I & V SOURCES

constant V source

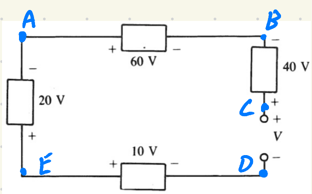
sinusoidal V source

constant I source

anode is longer

DC Battery

▷ LOOP RULE EXAMPLE



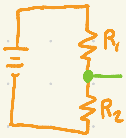
$V_{AB} + V_{BC} + V_{CD} + V_{DE} + V_{EA} = 0$

$60 + (-40) + V + (-10) + 20 = 0$

OHM'S LAW

$V = IR$

EX. VOLTAGE DIVIDER

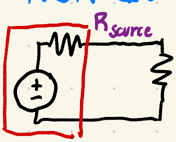


$$V_{out} = V_{in} \cdot \frac{R_2}{R_1 + R_2}$$

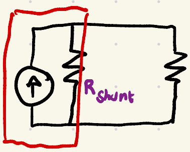
VOLTMETERS & AMMETERS

- Voltmeters should go in parallel & have resistance much greater than the element
- Ammeters should go in series & have resistance much smaller than the element

NON-IDEAL V&I SOURCES

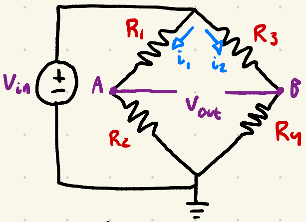


V source with internal resistance



I source with internal parallel resistance

▷ EX. WHEATSTONE BRIDGE



$$i_1 = \frac{V_{in}}{R_1+R_2}$$

$$i_2 = \frac{V_{in}}{R_3+R_4}$$

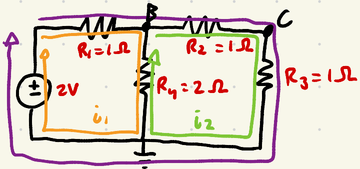
$$V_A = V_{in} - i_1 R_1 = V_{in} - \frac{V_{in} R_1}{R_1+R_2}$$

$$V_B = V_0 - i_2 R_3 = V_{in} - \frac{V_{in} R_3}{R_3+R_4}$$

$$V_A - V_B = \left(\cancel{V_0} - \frac{V_0 R_1}{R_1+R_2}\right) - \left(\cancel{V_0} - \frac{V_0 R_3}{R_3+R_4}\right)$$

$$= V_0 \left(\frac{R_3}{R_3+R_4} - \frac{R_1}{R_1+R_2}\right)$$

▷ EX. LOOP METHOD



$2 - i_1 R_1 - i_2 R_2 - i_2 R_3 = 0$

$(i_1 - i_2) R_4 - i_2 R_2 - i_2 R_3 = 0$

$\Rightarrow 2 - i_1(1) - i_2(1) - i_2(1) = 0 \Rightarrow 2 = i_1 + 2 i_2 \Rightarrow \boxed{i_1 = 2(1 - i_2)}$

$\Rightarrow \big(2(1-i_2) - i_2\big)(2) - i_2(1) - i_2(1) = 0 \Rightarrow i_2 = \frac{1}{2} A$

$i_1 = 2(1 - 0.5) = 1A$

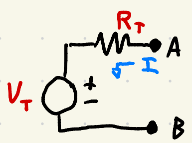
$V_B = 2V - i_1 R_1 = 1V$

$V_C = 1 - (0.5)(1) = 0.5\ V$

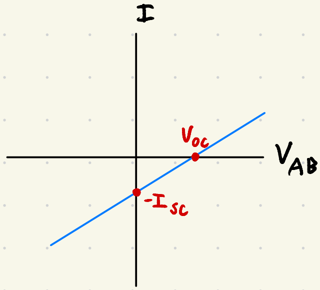
Thévenin & Norton

▷ THEVENIN

- An unknown linear circuit can be characterized by its open circuit voltage (V_{oc}) & short circuit current (I_{sc}).
- Any linear circuit can be replaced with an equivalent circuit w/ only a V source & a resistor.



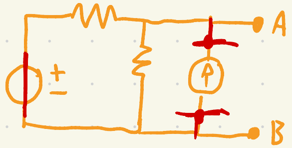
$$R_T = \frac{V_{oc}}{I_{sc}}$$



$V = V_T - IR_T$

$$I = \frac{(V - V_T)}{R_T} = \frac{V}{R_T} - \frac{V_T}{R_T}$$

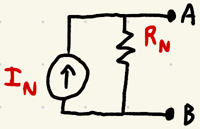
- The equivalent resistance R_T of a linear circuit is the R if you short all V sources & cut all I sources



$$V_{oc} = I_{sc} R_T$$

▷ NORTON

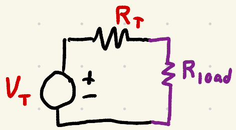
- Any linear circuit can also be replaced with an I source & a resistor in parallel.



- $R_T = R_N$ for any linear circuit

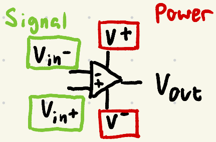
▷ MAX POWER

- Max power delivery is when $R_{load} = R_T$.



Amplification

▷ OP-AMPS



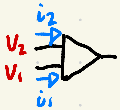
The output strength is proportional to the difference in signal voltages.

$$V_{out} = A \cdot (V_{in^+} - V_{in^-})$$

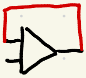
Amplification amount

The output voltage is bounded / clipped by the power voltages.

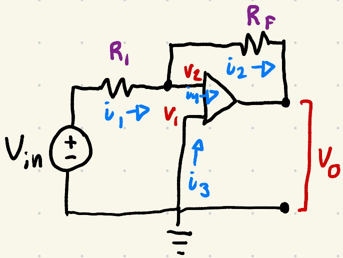
▷ IDEAL OP-AMP



- In an ideal op-amp,
  $V_2 = V_1$ &
  $i_1 = i_2 = 0$.
- $\therefore$ ∞ input resistance, 0 output resistance
- To achieve this, you can use a negative feedback loop:



▷ INVERTING AMP



It is known that

$i_3 = i_4 = 0 \quad \therefore \quad i_1 = i_2$

$V_1 = V_2 = 0$

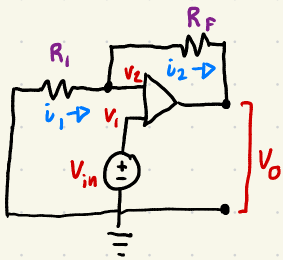
Ohm's Law:

$i_1 = \frac{V_{in}}{R_1} \qquad i_2 = \frac{V_o}{R_F}$

So

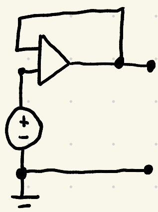
$$V_o = -V_{in}\left(\frac{R_F}{R_1}\right)$$

▷ NON-INVERTING AMP



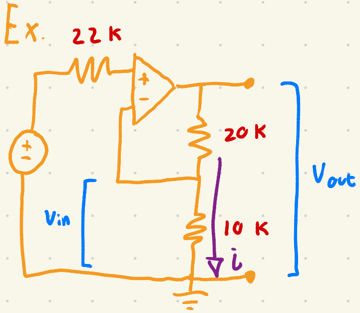
$$V_o = V_{in}\left(1 + \frac{R_F}{R_1}\right)$$

▷ VOLTAGE FOLLOWER



High input resistance, low output resistance

Ex.

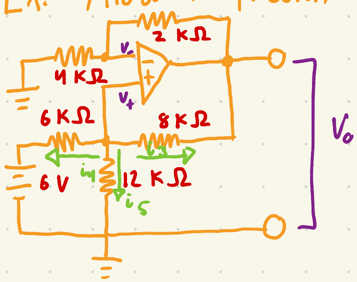


$V_{in} = i(10K)$

$V_{out} = i(30K)$

$\text{gain} = \frac{V_{out}}{V_{in}} = 3$

Ex. Midterm problem #1



$\boxed{1}$ Voltage divider across 4 KΩ & 2 KΩ $\rightarrow V_- = \frac{2}{3} V_o$

$\boxed{2}$ $i_3 = \frac{V_+ - V_o}{8\ K\Omega}$, $i_4 = \frac{V_+ - 6\ V}{6\ K\Omega}$, $i_5 = \frac{V_+}{12\ K\Omega}$

Because i into + of op-amp is 0, $i_3 + i_4 + i_5 = 0$

$$\frac{V_+ - V_o}{8\ K\Omega} + \frac{V_+ - 6\ V}{6\ K\Omega} + \frac{V_+}{12\ K\Omega} = 0$$

$\boxed{3}$ But, $V_+ = V_-$, and $V_- = \frac{2}{3} V_o$ from $\boxed{1}$, so

$V_o = 3\left(\frac{2}{3} V_o\right) - 8 \rightarrow V_o = 8\ V$

AC

$$F(t) = A \sin(\omega t + \varphi)$$

- F can be V or I
- A is amplitude
- ω is angular frequency (rad/s)
  - ν is frequency (Hz); $\omega = 2\pi\nu$
- φ is phase angle

▷ COMPLEX NUMBERS

like i, but i is used for current

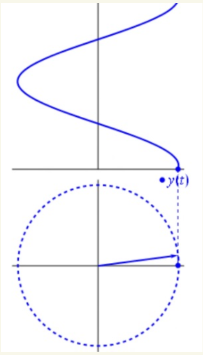
- $z = x + jy$
- Complex conjugate: for $z = a + bj$, conjugate $z^* = a - bj$

- Polar to complex rectangular: $Re^{j\theta} = R\cos\theta + Rj\sin(\theta)$
- Complex rectangular to polar: $R = \sqrt{x^2 + y^2}$, $\theta = \tan^{-1}\left(\frac{y}{x}\right)$

you may need to add/subtract π

▷ PHASORS

- A time-varying sinusoidal function
  $F(t) = A\sin(\omega t + \varphi)$
  can be represented independent of time by a phasor
  $\mathbf{F} = Ae^{j\varphi}$
  ^ phasors are in bold
- Phasors carry amplitude & phase info, not frequency



$$\mathbf{F} = Ae^{j\varphi} \equiv A\angle\varphi \equiv A\cos\varphi + jA\sin\varphi$$

- To convert to time domain, multiply by $e^{j\omega t}$ & take real part
  $\mathbf{F} = 5e^{j37^\circ} \Rightarrow$
  $F(t) = \mathrm{Re}(5e^{j37^\circ}e^{j\omega t}) = \mathrm{Re}(5e^{j(\omega t + 37^\circ)})$
  $= \mathrm{Re}(5\cos(\omega t + 37^\circ) + 5j\sin(\omega t + 37^\circ)) = 5\cos(\omega t + 37^\circ)$

- To get amplitude:
  $|\mathbf{V}| = \sqrt{x^2 + y^2} = \sqrt{\mathbf{V}\mathbf{V}^*}$

- Adding & subtracting: operate on real & imaginary components
- Multiplying & dividing: operate on polar coordinates

▷ DIFFERENTIATION

Given $v(t) = \mathbf{V}$,

$$\frac{dv}{dt} = j\omega\mathbf{V}$$

Capacitors

Capacitance:

$$C = \frac{K\varepsilon_0 A}{d}$$

- K: dielectric constant
- ε_0: permittivity of free space = $8.854 \cdot 10^{-12}$
- A: plate surface area
- d: Distance between plates

$$Q = CV$$

- At DC equilibrium, treat capacitor as open circuit $(I = 0)$
- At high frequency, treat capacitor as a short

$$Q = CV \rightarrow \frac{dQ}{dt} = C\frac{dV}{dt}$$

$$I = C\frac{dV}{dt}$$

$$P = \frac{1}{2}CV^2$$

▷ CAPACITORS UNDER AC

- $I = C\frac{dV}{dt} = CV_0 w \cos(wt)$
- Voltage lags current by 90°
  ICE - Current before Field in Capacitor

▷ MULTIPLE CAPACITORS

- Series: $C_{eq} = \dfrac{1}{\frac{1}{C_1} + \frac{1}{C_2}}$
- Parallel: $C_{eq} = C_1 + C_2$

Inductors

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

- Series: $C_{eq} = C_1 + C_2$
- Parallel: $C_{eq} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2}}$

(like resistors)

- In DC at equilibrium, treat inductor as short circuit ($V=0$)
- At high frequency, treat inductor as open circuit

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

Voltage leads current by 90°
ELI - Field before current in Inductor
ICE - Current before Field in Capacitor

AC Power

$P = IV$, so if I & V are out of phase, P is sinusoidal.

$$P_{avg} = \frac{1}{T}\int_0^T I_0 \cos(\omega t + \varphi_2)\, V_0 \cos(\omega t + \varphi_1)\, dt$$

$$P_{avg} = \frac{V_0 I_0}{2}\cos(\varphi_1 - \varphi_2)$$

- For capacitor-only & inductor-only circuits: $P_{avg} = 0$
- For resistor-only circuits: $P = \frac{1}{2R} V_0^2$

- In phasor notation, $\text{Avg}(vi) = \frac{1}{2}\text{Re}(vi^*)$

▷ RMS

To equate DC & AC power, we define V_{rms} & I_{rms}.

$$V_{RMS} = \frac{1}{\sqrt{2}} V_0$$

$$I_{RMS} = \frac{1}{\sqrt{2}} I_0$$

$$P_{avg} = I_{RMS} V_{RMS}$$

▷ IMPEDANCE & REACTANCE

Impedance is a phasor made up of a resistive part and a reactive part.

$$Z = R + jX$$

For a capacitor,

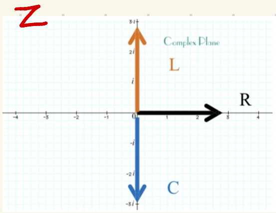
$\bar{i} = C \frac{dV}{dt}$

in phasor notation this is:

$\dot{i} = C \cdot j\omega \cdot V$

So:

$$\frac{V}{i} = \frac{1}{j\omega C} = Z$$



CAPACITATIVE IMPEDANCE

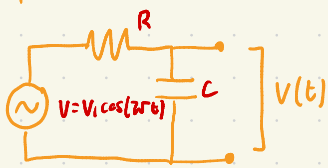
$X_C = \frac{-1}{\omega C} \quad \triangleright \quad Z_C = \frac{-j}{\omega C}$

INDUCTIVE IMPEDANCE

$X_L = \omega L \quad \triangleright \quad Z_L = j\omega L$

Example RC-AC Circuits

Ex.



$$\frac{V - V(t)}{R} - I_C = 0$$

$$\frac{V_1\cos(\omega t) - V(t)}{R} - C\frac{dV(t)}{dt} = 0$$

$$\frac{V(t)}{R} - \frac{V_1\cos(\omega t)}{R} + C\frac{dV(t)}{dt} = 0$$

Instead of solving this diff. eq. we can switch to phasors:

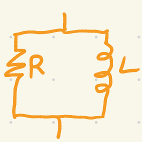
since $\varphi = 0$

$$\frac{V}{R} - \frac{V_1}{R} + C\cdot j\underbrace{\omega}_{\text{treat as a constant}} V = 0 \Rightarrow V = \frac{V_1}{1 + j\omega RC}$$

Treating it as an impedance voltage divider:

$$V_{out} = V_1\frac{Z_C}{Z_R + Z_C} = V_1\frac{\frac{1}{j\omega C}}{R + \frac{1}{j\omega C}} = V_1\underbrace{\frac{1}{1 + j\omega RC}}_{\text{Phasor}}$$

Ex.

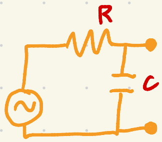


$$Z = \frac{1}{\frac{1}{Z_R} + \frac{1}{Z_L}} = \frac{1}{\frac{1}{R} + \frac{1}{j\omega L}}$$

Filters

- A Filter passes desired frequencies and rejects others.
  - Low pass: allows low frequencies
  - High pass: allows high frequencies
  - Band pass: allows frequencies in a desired range

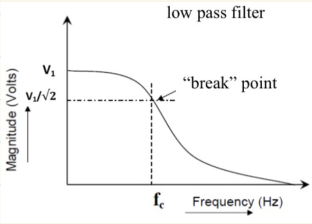
Ex. passive low pass filter



$$V_{out} = V_i \frac{\frac{1}{j\omega C}}{R + \frac{1}{j\omega C}} = V_i \frac{1}{1 + j\omega RC}$$

$$|V_{out}| = \sqrt{V_{out} V_{out}^*} = \sqrt{\left(\frac{V_i}{1+j\omega RC}\right)\left(\frac{V_i}{1-j\omega RC}\right)} = V_i \frac{1}{\sqrt{1+\omega^2 (RC)^2}}$$

slope: 20 dB/decade



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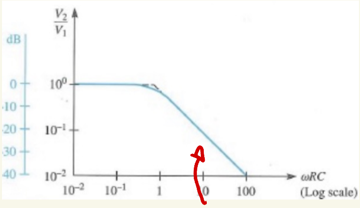
Log-log plot



Slope is in dB per decade

Decibels:

$$dB = 20 \log_{10} \frac{V}{V_0}$$

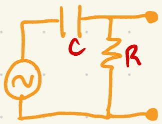
Reference Signal

Important point @ $\omega RC = 1$

↳ $|V_{out}| = \frac{1}{\sqrt{2}} V_i$

↳ Define break point $\omega_B = \frac{1}{RC}$

Ex. High pass Filter

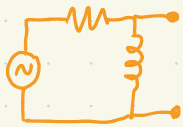


$$V_{out} = V_i \frac{R}{R + \frac{1}{j\omega C}} = V_i \frac{j\omega RC}{1 + j\omega RC}$$

$$\omega_B = \frac{1}{RC}$$

$$|V_{out}| = V_i \frac{\omega RC}{\sqrt{1 + \omega^2 (RC)^2}}$$

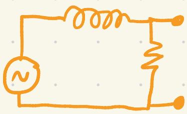
Ex. RL high pass filter



$$|V_{out}| = V_i \frac{1}{\sqrt{\left(\frac{R}{\omega L}\right)^2 + 1}}$$

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

Ex. RL low pass Filter



(voltage divider)

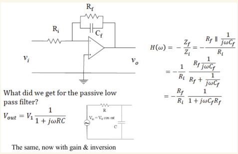
$$V_{out} = V_{in} \frac{R}{R + j\omega L} = \frac{R(R - j\omega L)}{R^2 - \omega L}$$

$$|V_{out}| = \sqrt{V_{out} V_{out}^*} = V_{in} \sqrt{\frac{R^2 (R - j\omega L)(R + j\omega L)}{(R^2 - \omega L)^2}} = V_{in} \sqrt{\frac{R^2 (R^2 - \omega^2 L^2)}{(R^2 - \omega L)^2}}$$

$=$

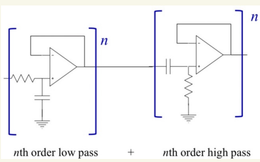
ACTIVE FILTERS

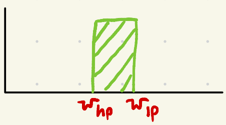
- You can use op amps to make active filters



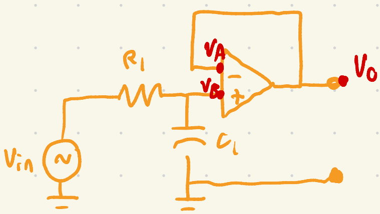
- Putting active filters in series adds the slopes of the log-log curves

- You can combine active high & low pass filters to make a band pass filter.





Ex. Low Pass Active Filter

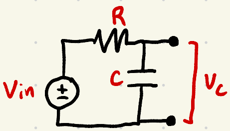


$V_o = V_A$, and $V_A = V_B$ (ideal op amp), so $V_o = V_B$
But this is just a voltage divider so

$$V_o = V_{in}\frac{\frac{1}{j\omega C}}{R + \frac{1}{j\omega C}} = V_{in}\frac{1}{1 + j\omega RC}$$

Transient Response

Step response: given an instantaneous connection of a power source, determine $V(t)$



- Initial conditions: $V_c(0) = 0$

$$\left.\begin{array}{l} q_c(t) = C\,V_c(t) \rightarrow \dfrac{dq_c(t)}{dt} = I(t) = C\dfrac{dV_c(t)}{dt} \\ \text{loop rule} \\ V_{in} - I(t)R - V_c(t) = 0 \rightarrow \dfrac{V_{in} - V_c(t)}{R} = i(t) \end{array}\right\} \dfrac{V_{in} - V_c(t)}{R} = C\dfrac{dV_c(t)}{dt}$$

$$\rightarrow \frac{dt}{RC} = \frac{dV_c(t)}{V_{in} - V_c(t)}$$

$$\int \frac{dt}{RC} = \int_0^{V_c(t)} \frac{dV_c(t)}{V_{in} - V_c(t)}$$

Let $u = V_{in} - V_c(t)$; $dV_c = -du$

$$= \int_{V_c=0}^{V_c=V_c(t)} -\frac{du}{u}$$

$$= -\ln(u)\Big|_0^{V_c(t)} = -\ln(V_{in} - V_c(t))\Big|_0^{V_c(t)}$$

$$= -\ln(V_{in} - V_c(t)) - \ln(V_{in} - 0)$$

$$\rightarrow \frac{V_{in} - V_c(t)}{V_{in}} = e^{-t/RC}$$

$$V_c(t) = V_{in}\left(1 - e^{-t/RC}\right)$$

Time constant $\tau = RC$: ohms × farads (secs)

After	1 time constant,	63% charged
	2	86.5%
	3	95%

▷ RC CIRCUIT WITHOUT DIFF EQ

- First equation: loop rule relating V_{in} & V_{out}
- Second equation: general form $A + Be^{-t/\tau}$
- Third equation: initial conditions $V_c(0) = ?$

$$\left.\begin{aligned} &\frac{V_{in} - V_c(t)}{R} = C\frac{dV_c(t)}{dt} \\ &\text{and} \\ &V_c(t) = A + Be^{-t/\tau} \end{aligned}\right\} \frac{V_{in} - A - Be^{-t/\tau}}{R} = \frac{-BC}{\tau}e^{-t/\tau}$$

equate coefficients:

$$\frac{V_{in} - A}{R} = 0 \rightarrow V_{in} = A$$

$$\frac{-B}{R} = -\frac{BC}{\tau} \rightarrow \tau = RC$$

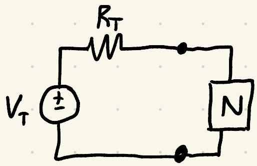
Then, use initial conditions to find B:

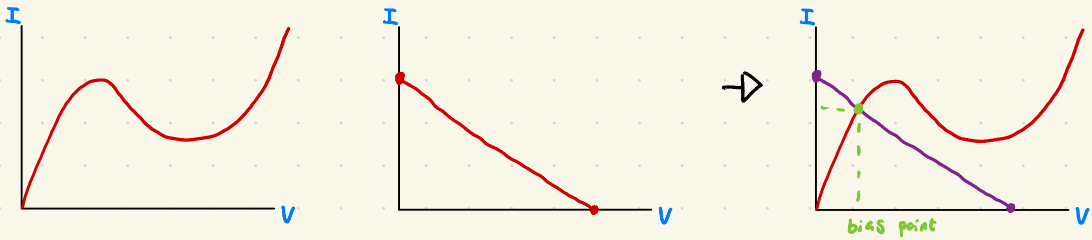
$$V_c(0) = 0 = V_{in} - Be^{-0/RC} \rightarrow B = -V_{in}$$

Nonlinear Elements

▷ LOAD LINE

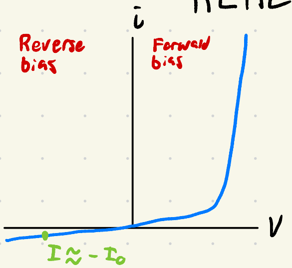
- A nonlinear element can have any I vs. V relationship
- When connected to a linear circuit I & V are constrained linearly
- The operating conditions are the intersections between the complex & linear curves, called the BIAS POINT





Diodes

REAL DIODE



$I = I_0\left(e^{qV/KT} - 1\right)$

q = charge of e^-

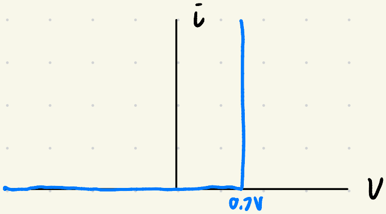
V = voltage in

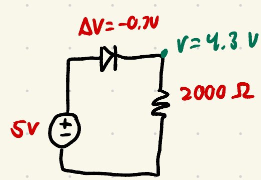
K = Boltzmann's constant

T = temp. in kelvin

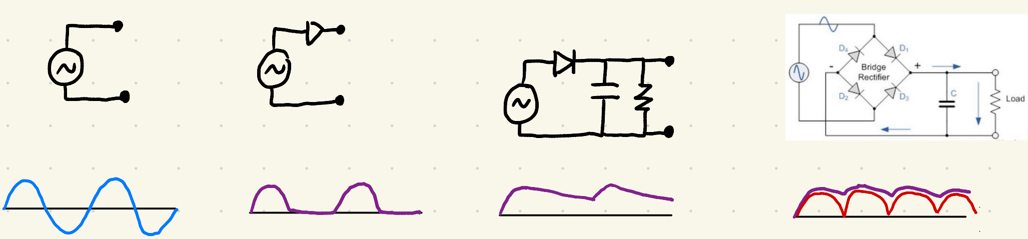
IDEAL DIODE

- Large signal diode: current only flows when voltage is high enough (usually ≥ 0.7 V); voltage drop when ON is 0.7 V
- Assume ▷| means large signal diode w/ drop of 0.7 V



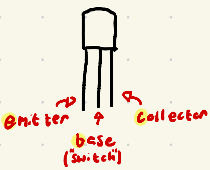


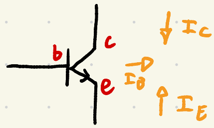
▷ RECTIFIERS

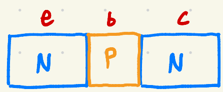


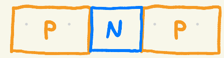
Bipolar Junction Transistors

- A BJT is a <u>current amplifier</u>









$$V_{CE} = V_{BE} + V_{CB}$$

$$i_e + i_b + i_c = 0$$

ALL i's are flowing inwards

Current transfer ratio:

$i_c = -\alpha i_E$ $\quad \alpha > 0.98$ usually $\quad \beta = \frac{\alpha}{1-\alpha}$

Current gain:

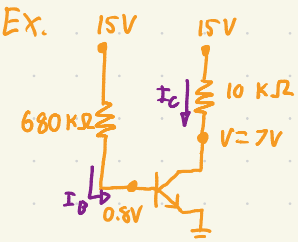
$i_c = \beta i_B$ $\quad 50 < \beta < 1000$ usually $\quad \alpha = \frac{\beta}{1+\beta}$

Base-Emitter voltage:

$V_{BE} = 0.7\ V$

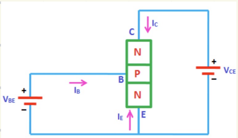
* IN ACTIVE MODE

Ex.

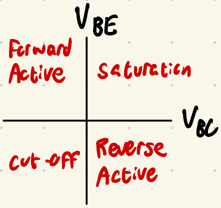


$\beta = \frac{I_C}{I_B}$

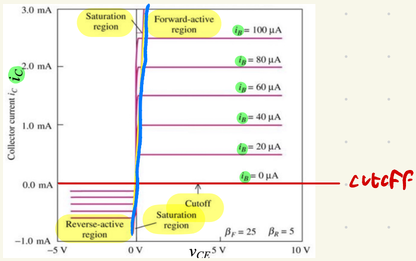
▷ COMMON EMITTER



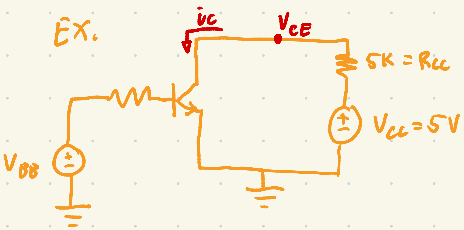
E is connected in a loop with B's voltage source



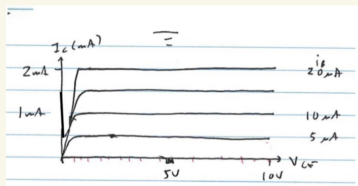
Saturation region



Ex.



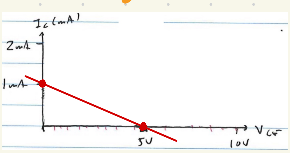
You are given the following spec sheet:



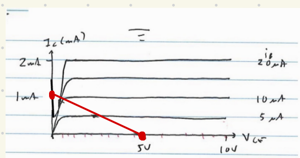
Find I_C, V_{CE} for $V_{BB} = 0, 1.2, 2.7V$.

$\therefore \ \beta = 100$

I_C & V_{CE} are dictated by a Thevenin circuit, so



→



Case 1, $V_{BB} = 0$

below cutoff; $I_C = 0$

intersect: $V_{CE} = 5V$

case 2, $V_{BB} = 1.2V$

$I_B = \frac{1.2 - 0.7}{100K} = 5\ \mu A$; $I_C = \beta I_B = 0.5\ mA$

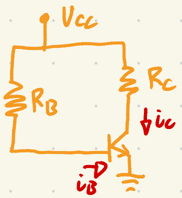
$V_{CE} = V_{CC} - I_C R_C = 5 - (0.5\ mA)(5K) = 2.5V$ (intersect)

AS V_{BB} increases, I_C will increase at a fast rate, decreasing V_{CE}!

▷ BIASING

- Resistors can be used to "bias" a transistor to rest at an "operating point" when no signal is applied

Ex. Find R_B & R_C such that $I_C = 1$ mA. $\beta = 100$, $V_{cc} = 10$ V.



$I_C = \beta I_B \rightarrow I_B = 10^{-5}$ A

$V_B = 0.7$ V due to voltage drop

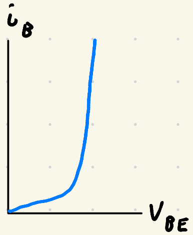
$I_B = \frac{V_{cc} - V_B}{R_B} \rightarrow 10^{-5} A = \frac{10V - 0.7V}{R_B} \rightarrow R_B = 9.3 \cdot 10^5 \,\Omega$

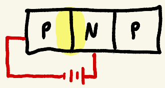
To choose V_c, it should be > 0 to keep collector junction reverse biased, but cannot be larger than V_{cc}. So $0 < V_c < 10$. To keep operating point reasonable, choose midpoint of $V_c = V_{cc}/2 = 5$ V.

$I_c = \frac{V_{cc} - V_c}{R_c} \rightarrow R_c = 5000 \,\Omega$

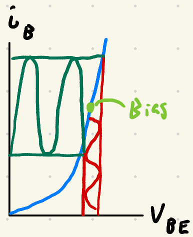
▷ SMALL SIGNAL MODEL

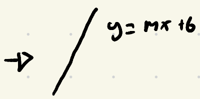
- When configured with a common emitter, i_B & V_{BE} have the exponential relationship of a diode





- When a small AC signal is applied, you can approximate BJT response as linear
  * AC signal on top of a DC bias





Note:

i_B - total signal

I_B - DC bias

i_b - small signal

$i_B = I_B + i_b$

$$i_B = \underbrace{I_B}_{\text{DC bias}} + \overbrace{\left[\frac{di_B}{dV_{BE}}\right|_{Q-\text{point}}]}^{\text{linear approximation}} \cdot \underbrace{(V_{be})}_{\text{small signal, not including bias}}$$

$$\frac{di_B}{dV_{BE}} = \frac{e}{KT} i_B = \frac{e}{KT} I_B$$

$$i_E \approx I_{ES}\left(e^{\frac{eV_{BE}}{KT}}\right)$$

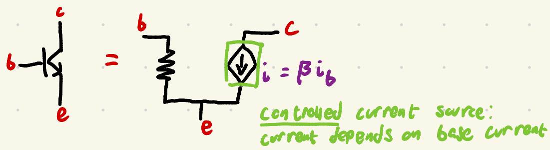
$$i_B \approx \frac{I_{ES}}{\beta+1}\left(e^{\frac{eV_{BE}}{KT}}\right)$$

$$i_b = \frac{V_{be}}{\boxed{KT/eI_B}}$$

← This follows form V=IR

← This is the "resistance" you can model with!

And thus, we can treat the BJT under small signal as a resistor.



The resistance of the model resistor is

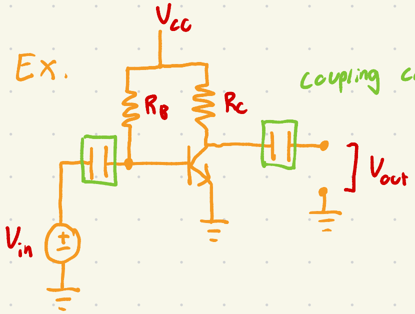
$$r_\pi = \frac{kT}{eI_B} \approx \frac{26\,\text{mV}}{I_B}$$

Note:

With respect to small signals, treat DC Voltage sources as shorts, and DC current sources as open circuits.

Treat capacitors as small signal shorts

Ex.



coupling capacitors

THEREFORE V_{in} does nothing

$V_{cc} = 15\ V$
$\beta = 100$
$R_B = 3M\ \Omega$
$R_c = 10K\ \Omega$

$\boxed{1}$ Find DC operating point

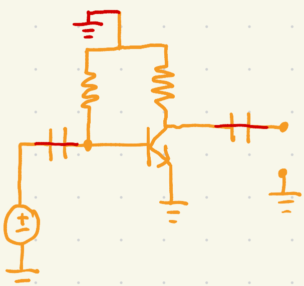
$$I_B = \frac{15 - 0.7}{3M} = 4.8\ \mu A$$

$$\rightarrow I_c = \beta I_B = 480\ \mu A$$

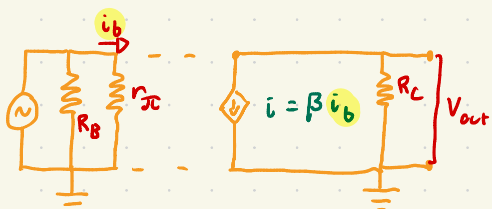
$$V_c = V_{cc} - I_c R_c = 15 - (.48\ mA)(10\ k) = 10.2\ V$$

$$V_{cB} = 10.2 - 0.7 = 9.5\ V$$

$\boxed{2}$ Draw equivalent small signal circuit



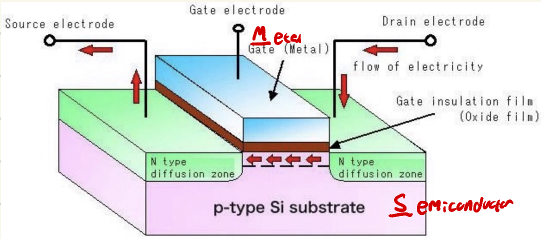
$\rightarrow$



$$V_{out} = -i_c R_c = -\beta i_b R_c = -\beta \frac{V_{in}}{r_\pi \| \cancel{R_B}} R_c \approx -\beta \frac{V_{in}}{r_\pi} R_c$$

- Find r_π using steady state I_B

MOSFETS



Metal

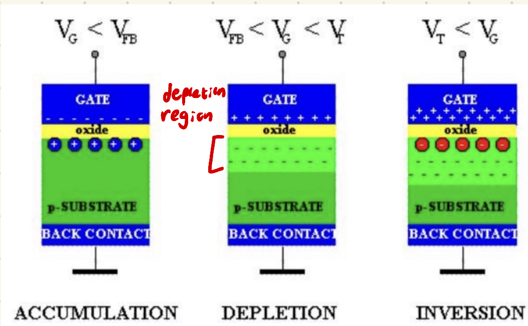
Oxide

Semiconductor

Treat M-O-S sandwich as a capacitor w/ one plate as a semiconductor

Source (emitter) | Gate (base) | Drain (collector)

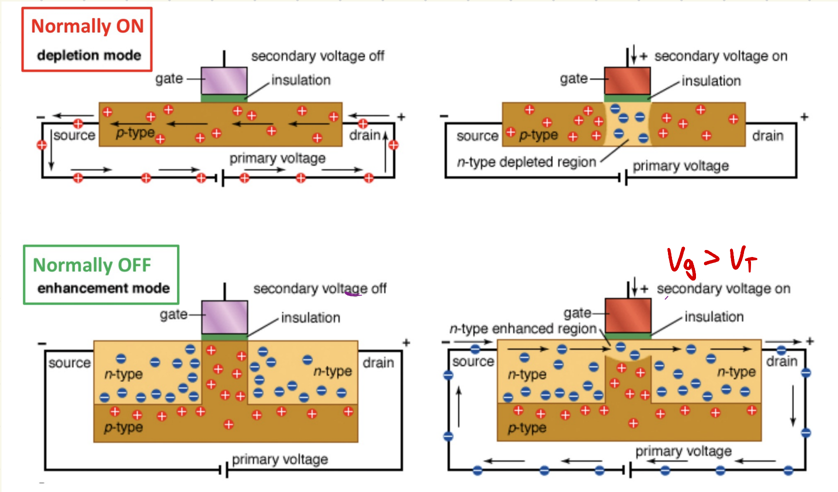
i



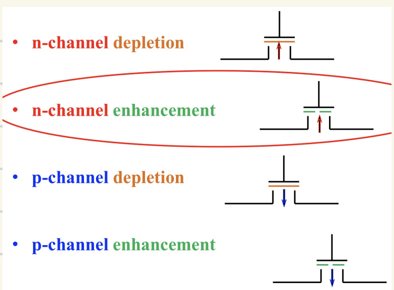
depletion region

- Accumulation: gate is negatively charged, mobile charge carriers (holes) accumulate and semiconductor is conductive
- Depletion: gate is positive, mobile holes are pushed away, depletion region grows and conductivity lessens
- Inversion: as gate becomes more positive, electrons become mobile charge carriers and semiconductor becomes conductive again

- V_T is the threshold voltage at which the transistor starts to turn on

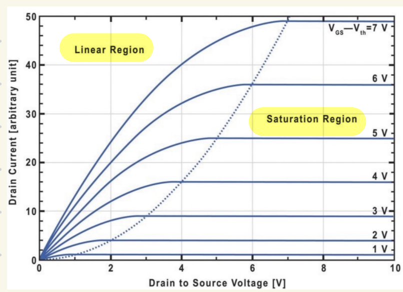


$V_g > V_T$



normally off

normally on



$\boxed{1}$ Find V_{GS}

$\boxed{2}$ Find Thevenin load line

$\boxed{3}$ Overlay load line with spec graph to get i_D & V_D

$\boxed{4}$ Find K with $I_{D,sat} = \frac{1}{2} K (V_{GS} - V_T)^2$

$\boxed{5}$ Find $g_m = K(V_{GS} - V_T)$

In triode (linear) region:

$$I_D = K\left[(V_{GS} - V_T)V_{DS} - \frac{1}{2}V_{DS}^2\right]$$ in triode/linear region

$$I_{D,sat} = \frac{1}{2}K(V_{GS} - V_T)^2$$ in saturation region

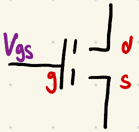
A MOSFET is in linear region when:

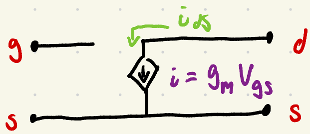
$V_{GS} \geq V_T$ &&

$V_{GD} = V_{GS} - V_{DS} < V_T$

▷ SMALL SIGNAL

- A MOSFET under small signal is a voltage-controlled current source.





- The relation between V_{gs} & i_{ds} is:

$$i_{ds} = g_m V_{gs}$$

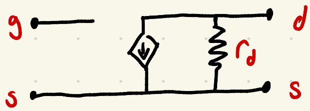
Where g_m is the transconductance

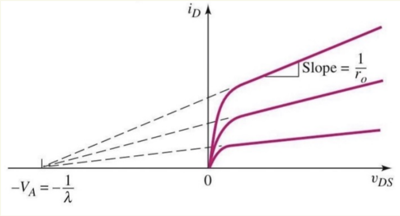
$$g_m = K(V_{GS} - V_T) = \frac{2I_{DS}}{V_{GS} - V_T}$$ * at Q-point

Find K from $I_{D,sat}$ & $(V_{GS} - V_T)$ eqn

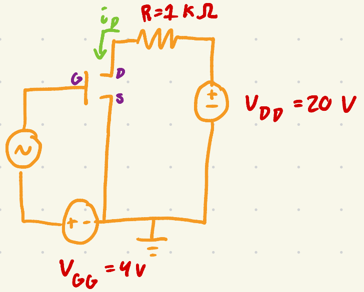
▷ RESISTANCE

- Real-life MOSFETS have output resistances, so model like this:





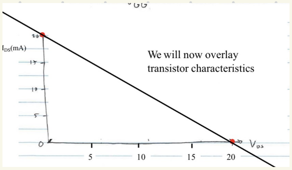
Ex. Amplifier



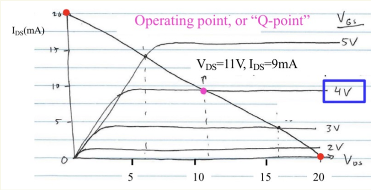
Thevenin:

$V_T = 20$ V

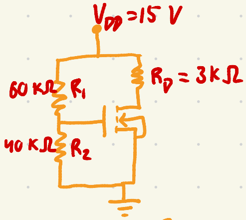
$i_{SC} = \frac{20}{1000} = 20$ mA



Overlay w/ MOSFET graph, seeing intersection w/ the curve w/ $V_{GS} = 4V$ (DC bias)



Ex.



$$V_{GS} = V_{DD} \cdot \frac{R_2}{R_1 + R_2} = 15 \cdot \frac{40}{100} = 6V$$

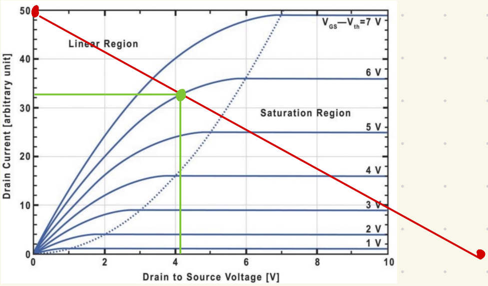
Voltage divider

Find load line:

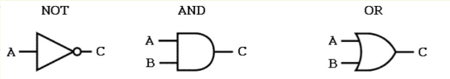
$V_{oc} = 15$ V

$I_{SC} = \frac{15V}{3k\Omega} = 5$ mA

overlay



Digital Logic



NOT

Input A	Output C
0	1
1	0

$\bar{A}$

AND

Inputs A	Inputs B	Output C
0	0	0
0	1	0
1	0	0
1	1	1

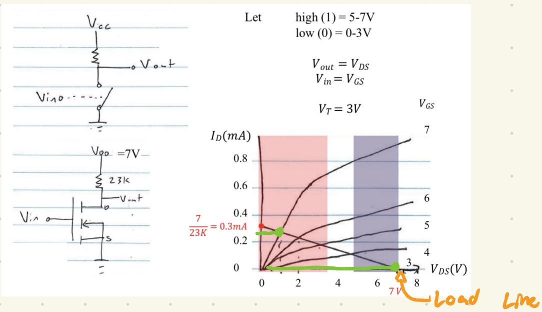
AB

OR

Inputs A	Inputs B	Output C
0	0	0
0	1	1
1	0	1
1	1	1

$A + B$

▷ NOT

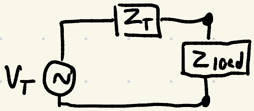


intersection < 3V
when input > 5V
intersection > 5V
when input < 3V

Impedance Matching

- Remember: max power transfer when $R_{load} = R_{Thevenin}$

- Voltage divider



$$V_{load} = V_T \frac{Z_{load}}{Z_T + Z_{load}}$$

$$I_{load} = \frac{V_T}{Z_T + Z_{load}}$$

Time averaged power

$$P_L = \frac{1}{2} Re(V_{load} I_{load}^*) = avg(v\,i)$$

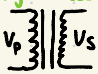
- The result of using calculus on the expanded equation is

Max power @ $X_{load} = -X_T$, $R_{load} = R_T$

@ $Z_{load} = Z_T^*$

Transformers

Primary   Secondary



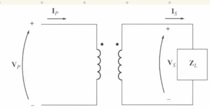
$$\frac{V_s}{V_p} = \frac{N_s}{N_p} \; ; \; \frac{i_s}{i_p} = \frac{N_p}{N_s}$$

\# turns of secondary

\# turns of primary

- Impedance:

$$Z_p = \left(\frac{N_p}{N_s}\right)^2 Z_L$$



$$\frac{v_S}{v_p} = \frac{N_s}{N_p} \; ; \; \frac{i_s}{i_p} = \frac{N_p}{N_s}$$

$$Z_L = \frac{V_s}{I_s}$$

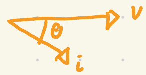
$$\boxed{Z_P = \frac{V_P}{I_P} = \frac{\left(N_P/N_s\right) V_s}{\left(N_s/N_P\right) I_s} = \left(N_P/N_s\right)^2 Z_L}$$

This is the "apparent" impedance of the primary

AC Power

$P = \text{Avg}(vi) = \frac{1}{2}\text{Re}(vi^*) = V_{rms} I_{rms} \cos\theta$

Power factor



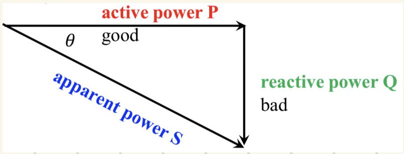
POWER TRIANGLE

all RMS

S (apparent power) $= VI = \frac{V^2}{|Z|}$

P (active power) $= VI \cos\theta$

Q (reactive power) $= VI \sin\theta$



MAKE P & Q NEGATIVE DEPENDING ON SIGN OF θ

V leads I for inductors

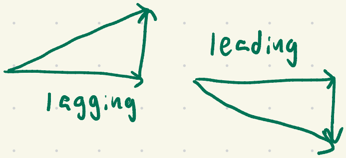
I leads V for capacitors

IF GIVEN Hz, REMEMBER $\omega = 2\pi f$

The W value given in a problem (load power) is P.
Divide by P.F. to get S.

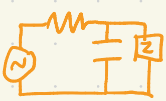
POWER FACTOR

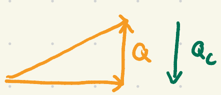
$P.F. = \frac{P}{S} = \cos\theta$



IMPEDANCE MATCHING

- You can make a "flat" triangle by inserting a capacitor/inductor to get rid of reactivity.





$Q_c = V_c I_c = V_c \frac{V_c}{\left|\frac{1}{j\omega C}\right|} = |V_c|^2 \omega C$

- NOT ON EXAM
  - RLC Circuits, quality Factor, bandwidth
  - Transient response analysis (except RC transient)
  - Flip flops
  - Optoelectronics

- Rumored to not be on exam
  - Digital circuits
  - Logic gates
  - MOSFETS