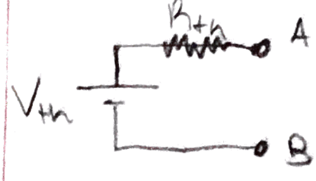
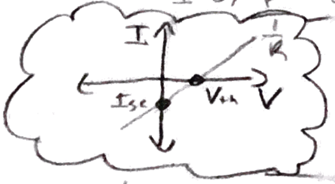


KVL: $V_{th} - IR_{th} - V_{AB} = 0$

$I=0$, open circuit so $V_{th} = V_{AB}$

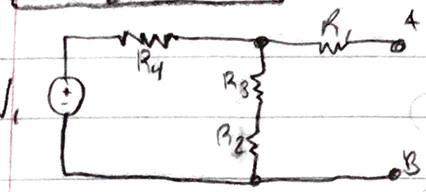


← parallel $R_1 \| R_2$

Thevinin Break down simple examples

Voltage divider

①

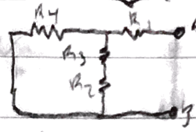


could find I_{sc} here but it'd take more work just connect AB and do KVL!

no current (leave AB open so no current goes to R_1)

KVL: $V_1 - I(R_2 + R_3 + R_4) = 0$ and $V_{AB} - I(R_2 + R_3) = 0$

no voltage (replace source w/ wire and connect AB)



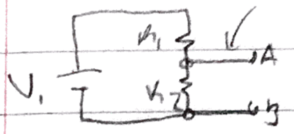
$\rightarrow R_{th} = \frac{(R_2+R_3)R_4}{(R_2+R_3)+R_4} + R_1$

and $V_{AB} = V_{th} = \left(\frac{R_2+R_3}{R_2+R_3+R_4}\right)V_1$

---

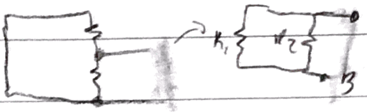
no resistor here what will be difference?

②



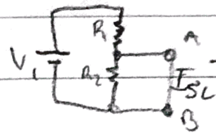
no current: $V_{AB} = V_{th} = V_1\left(\frac{R_2}{R_1+R_2}\right)$

no voltage:



$\rightarrow R_{th} = \frac{R_1 R_2}{R_2 + R_1}$

or find I_{sc}:



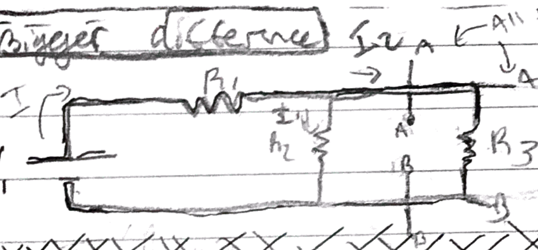
→ won't go to R_2 so $V_1 = I_{sc} R_2 \rightarrow I_{sc} = \frac{V_1}{R_2}$

then use $V_{th} = I_{sc} R_{th}$

Bigger difference

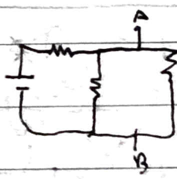
③

← All these are legal.



$\in R_{net} \neq R_{th}$

① find V_{AB}, which is the drop across R_3 if you just follow the wire or do



~~$V_{AB} = I_2 R_3$ have to find I_2 so lets find R_{th} to $V = IR_{net}$~~

~~JUST USE KVL:~~

← Voltage divider

$V_{th} = V_{AB} = V_1\left(\frac{R_{23}}{R_1+R_{23}}\right)$

notice its a voltage divider w/ one in parallel

Dont useful!

$V_1 - IR_1 - I_1 R_2 = 0$

$V_1 - IR_1 - I_2 R_3 = 0 \rightarrow V_{AB} = V_1 - IR_1$

- could use simplified loop to plug into I but voltage divider eq is much easier!

Quick Recap of Voltage divider

1) $V_{in} - I(R_1 + R_2) = 0$

2) $V_{AB} - I(R_2) = 0$

* plug I into an eq + solve for V_{AB}

$$\boxed{V_{AB} = V_{in}\left(\frac{R_2}{R_1 + R_2}\right)}$$

$R_{eq} = \frac{1}{\frac{1}{R_2} + \frac{1}{R_{in}}}$

as $R_{in} \to \infty$

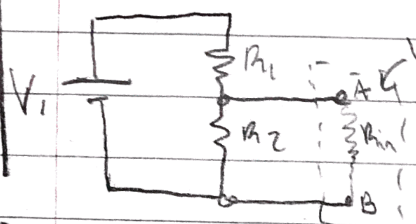
$R_{eq} \to R_2$

So you want Voltm to have high R

Input Resistance

- the measuring instrument becomes part of the circuit

Ex



ignore R_{in} and Voltmeter for a se its voltage divider so!

$$V_{AB} = V_1\left(\frac{R_2}{R_1 + R_2}\right) \quad (1)$$

this is what the meter will read out

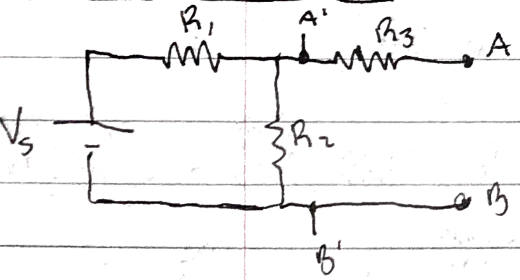
- But since its not a perfect voltmeter it has a R_{in}
- R_2 and R_{in} are in series so:

between R_{in} and R_2

$R_{net} = \frac{R_{in} \cdot R_2}{R_2 + R_{in}}$ → Plug this into (1) as R_2 bec its its eq Resistance

$$V_{AB} = V_1\left(\left(\frac{R_{in}R_2}{R_2 + R_1}\right)\frac{1}{R_1 + \left(\frac{R_{in}R_2}{R_2 + R_1}\right)}\right) = \frac{R_2 R_{in}}{R_1(R_{in} + R_2) + R_2 R_{in}}$$

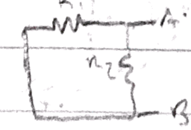
Cascade of Thevenin:



If you ignore R_3 and V_{AB} you can see A' B', $V_{A'B'}$ is just a voltage divider so we can use thevenin to simplify the left.

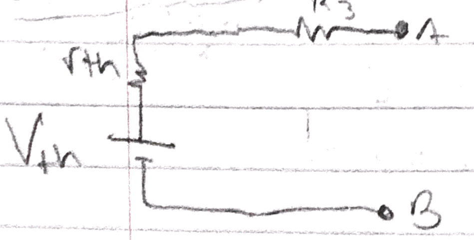
(1) $V_{A'B'} = V_{oc} = V_s \frac{R_2}{R_1 + R_2}$

for r_{th} replace V_s w/ wire



$R_1 \| R_2$ so $r_{th} = \frac{R_1 R_2}{R_1 + R_2}$

(2)

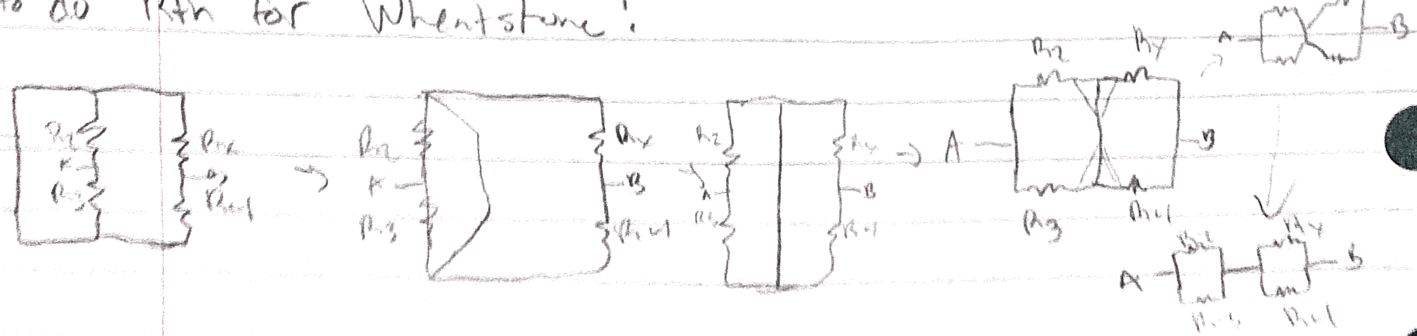


$R_{th} = r_{th} + R_3$

→ since theres no current and subsequently no drops across V_{th} + R_3

$V_{th} = V_{th}$

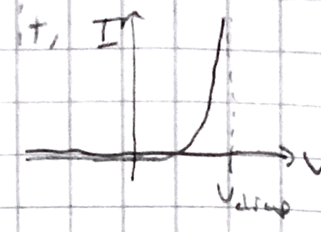
How to do Rth for Wheatstone:



6

[Diodes in Circuits]

- an ideal diode has $Z = \infty$ when $V < 0$ and $Z = 0$ when $V > 0$
- a real diode has a V_{drop} across it,



Shockley diode eq'n: $I = I_0\left[e^{\frac{eV}{k_B T}} - 1\right]$

easy approximation:

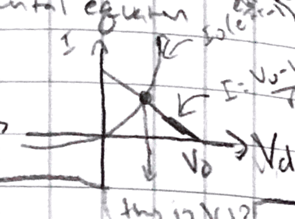
[if $V >> V_{drop}$ or $V_{drop} >> V$] → if $V < V_{drop}$: $I = 0$

if $V \geq V_{drop}$: $\boxed{KVL}$ $V = V_{drop} - IR \Rightarrow I = \frac{V_0 - V_{drop}}{R}$

solving for V_d CAN'T, transcendental equation

[If we use Shockley] → $V_0 - IR - V_d = 0 \rightarrow I = \boxed{\frac{V_0 - V_d}{R} = I_0\left(e^{\frac{eV_d}{kT}} - 1\right)}$

*solve w/ Newtons method or "load line"

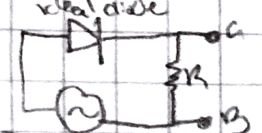


[origin of V_{drop} w/ equations I don't understand] $I = \underset{\text{constant}}{C}\, e^{\frac{-\Delta E}{k_B T}}\left[e^{\frac{eV}{k_B T}} - 1\right]$, when $\frac{eV}{k_B T} >> 1$, $\frac{k_B T}{e}(\ln I - \ln C) = V - \frac{\Delta E}{e}$ ← energy of gap

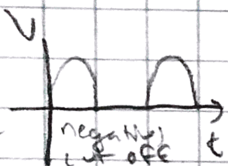
(I_0 above $Ce^{-\Delta E/k_BT}$)

[Making an AC adapter]

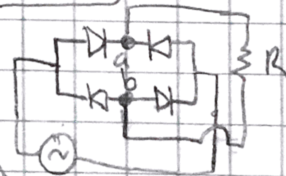
① ideal diode

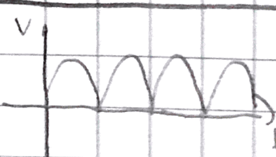


[$V > 0$ $Z = 0$; $V < 0$ $Z \to \infty$]



② let's get the cut off part

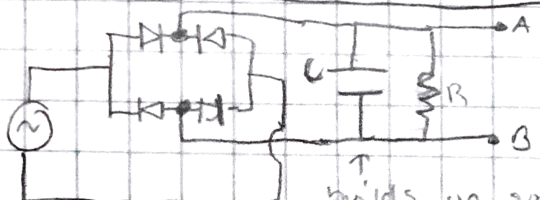




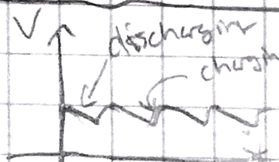
→ ⧏ blocked
→ ⊳| passed

to understand follow path from either side when

③



↑ builds up some but when it switches it discharges



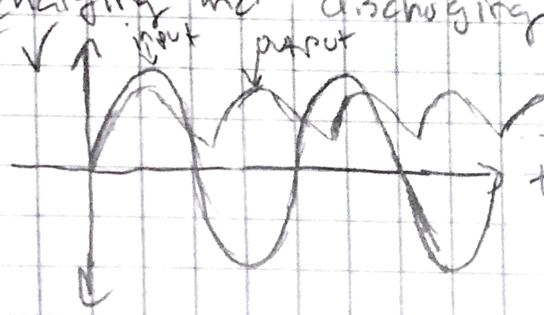
charges when
discharges when

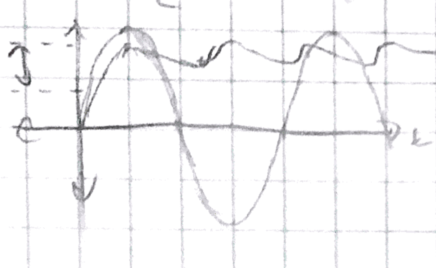
→ this is one way to filter out the signals.

But what is actually happening?

[at certain times the capacitor is charging and discharging] → [you don't want it to charge up quickly, to do this, you need] ← high capacitance ↙ scale up more charge

→ ω be high?, so it acts like wire or doesn't conduct much
↑
low f_c = ripple





← get this when you increase capacitance

Ripple factor of circuit?

form factor?

↓

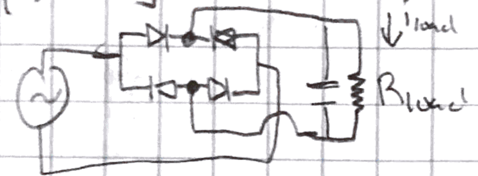
r: $\dfrac{\text{Voltage (rms) of output signal}}{\text{average value of signal}} = \dfrac{V_{rms(AC)}}{V_{DC}}$ ← "AC part" ← "direct current part"

bec/ in rectifiers we care about R_{load}

getting equations: $P = \frac{1}{T}\int \frac{v(t)^2}{R}dt = \frac{V_{rms}^2}{R} \rightarrow V_{rms}^2 = \frac{1}{T}\int_0^T v^2(t)dt$

$V_{DC} = \frac{1}{T}\int_0^T v(t)dt$

usually output voltage V_{rms} or V_{Load} of the load



*you can say: $i_L(t) = \frac{v_L(t)}{R_L}$ and $I_{DC} = \frac{V_{DC}}{R_L}$ and $I_{rms} = \frac{V_{rms}}{R_L}$

Lets think about ΔV drop of the capacitor thats causing these ripples

for small ripples you can approximate I_{load} to be constant → $Q = CV$, $I = C\frac{dV}{dt}$ → $\Delta V = \frac{I}{C}\Delta t$ $\begin{cases} \Delta t \approx \frac{1}{f} & \text{(half wave rectification)} \\ \text{or} & \\ \Delta t \approx \frac{1}{2f} & \text{(full wave rectification)} \end{cases}$

↓

capacitor begins charging again in less than a half cycle

$\boxed{\Delta V = \frac{I_{load}}{fC} \quad \text{or} \quad \Delta V = \frac{I_{load}}{2fC}}$

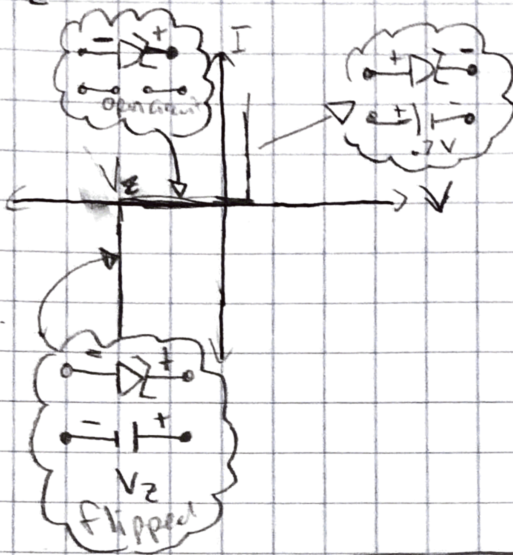
*Resistor causes capacitor to discharge "somewhat" between cycles (or half cycles for full wave rectification)

assuming a linear approximation it is conservative in design

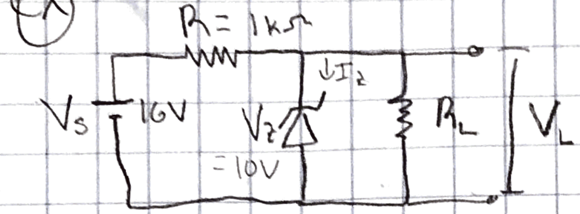
*I think I_{load} is current across the resistor bec/ the resistor is what is making its $\frac{dV}{dt}$ ↳ can't discharge anywhere else

8

Zener diode Practice Problems



EX



$R_L = 1.2k\Omega$: find state of zener diode by seeing voltage

$$V_L = V_Z = V_S \frac{R_L}{R_L + R} = 8.73V$$ so zener is OFF

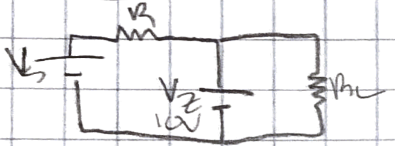
$$V_R = V_S - V_L = 16 - 8.73 = 7.27V$$

$I_Z = 0$, $P_Z = 0$

$R_L = 3k\Omega$:

$P_Z = I_Z V_Z$

$$V_L = V_{zener} = V_S \frac{R_L}{R_L + R} = 12V$$ so zener on



$V_{zener} = V_L = 10V$ (zener regulates voltage)

$V_R = V_S - V_L = 16 - 10 = 6$

$I_R = \frac{V_R}{R} = 6mA$

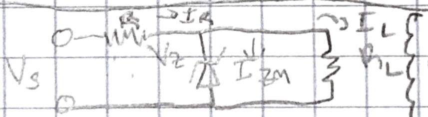
$I_L = \frac{V_L}{R_L} = \frac{10}{3k\Omega} = 3.33$

$I_Z = I_R - I_L = 6 - 3.33 = 2.67mA$

to find the minimum load resistance such that if $R_L > R_{Lmin}$, Zener is on and $R_L < R_{Lmin}$ Zener is off → $V_L = V_Z$, breakdown, $V_L = V_Z = V_S \frac{R_L}{R + R_L}$ → $\boxed{R_{Lmin} = R \frac{V_Z}{V_S - V_Z}}$

↳ also $I_{Lmax} = V_L / R_L = V_Z / R_{Lmin}$

Since zener diode regulates, there is a max resistance, (has an I_{mz} where it breaks down)



constant! KVL: $V_R = V_S - V_Z$

$I_R = \frac{V_R}{R}$

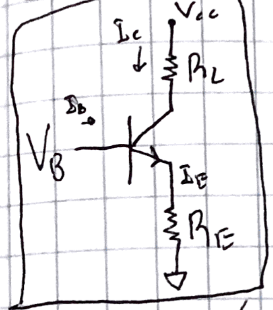
Once the diode is on: $I_Z = I_R - I_L$ (I_Z is limited to I_{ZM}) → $\boxed{I_{ZM} = I_R - I_{Lmin}}$

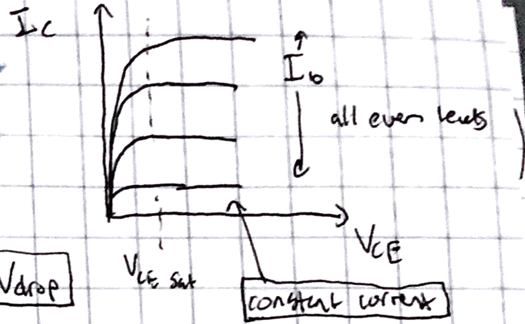
generally: $R_L = \frac{V_L}{I_L}$ ⇒ $\boxed{R_{Lmax} = \frac{V_Z}{I_{Lmin}} = \frac{V_Z}{I_R - I_{ZM}}}$

so zener is on when: $I_{Lmin} < I_L < I_{Lmax}$, $R_{Lmin} < R_L < R_{Lmax}$

Transistor example problems

5





BE loop $\quad V_B = V_{BE} + I_E R_E$

* if transistor is conducting then $\boxed{V_{BE} = V_{drop}}$

$\hookrightarrow V_B = V_{drop} + I_E R_E$

$\frac{\beta}{\beta+1} \approx 1$ if $\beta \gg 1$

think discrete levels

$I_c = \beta I_B$ (← only true for linear active region) then $I_c = \frac{\beta}{1+\beta} I_E \approx I_E$

then $\boxed{I_c \approx I_E = \frac{V_B - V_{drop}}{R_E}}$

* I_c is controlled by V_B, doesnt depend on load R_L *
(Current source bec/ its constant and doesnt change)

Q1 Given $R_E, R_L, V_{CE\,sat}$, whats the maximum current this source can provide. ($I_c \approx I_E$)

* remember $V_{CE} \geq V_{CE\,sat}$ *

$V_{cc} = V_{CE} + I_c R_L + I_E R_E \rightarrow V_{CE} = V_{cc} - I_c(R_L + R_E) \geq V_{CE\,sat}$

then $\boxed{I_c \leq \frac{V_{cc} - V_{CE\,sat}}{R_L + R_E}}$

Q2 Find R_E so a $I_c = 0.5A$ flows through the load, $V_B = 3.2V$

(assuming transistor action condition)

$I_c = .5A \rightarrow I_c \approx I_E \longrightarrow I_E = \frac{V_E}{R_E} = \frac{V_B - V_{drop}}{R_E}$

$\boxed{R_E = \frac{V_B - V_{drop}}{I_E} = 5.2\,\Omega}$

Q3 What is the maximum value of the load resistor with $I_c = 0.5$, $V_{cc} = 15V$

* or how big can you make R_L so it stays in linear active region *

$V_{cc} = I_c R_L + I_E R_E + V_{CE} \rightarrow V_{CE} = V_{cc} - I_c R_L - I_E R_E \geq V_{CE\,sat}$ $= .2V$

$R_L \leq \frac{V_{cc} - I_E R_E - V_{CE\,sat}}{I_c}$, ($R_E$ is from above), [if past saturation $I_c \approx I_E$] $= 24.4\,\Omega$

as R_L gets bigger it takes up a larger fraction of V_{cc} meaning V_{CE} gets lower pushing it into saturation

Q4 If $R_L = 10\,\Omega$ what value of V_B will put transistor into saturation?

as V_B gets bigger, I_B goes up causing a larger proportion to drop across R_E, which makes V_{CE}

• in linear active region $V_{CE} > V_{CE\,sat}$
• at saturation $V_{CE} = V_{CE\,sat}$
$I_E \approx I_L$

← actually look at load

$\rightarrow$ $V_{cc} = I_c R_L + I_E R_E + V_{CE} \approx I_E(R_L + R_E) + V_{CE}$

$\hookrightarrow I_E \approx \frac{V_{cc} - V_{CE}}{R_L + R_E}$

plug in $V_{CE\,sat}$ you can rearrange to assure ≤ is right

$V_B = V_{drop} + I_E R_E \approx \frac{V_{cc} - V_{CE}}{R_L + R_E} R_E + V_{drop}$

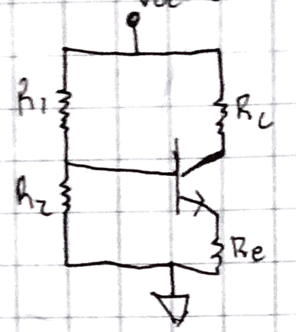
$\boxed{V_B \leq \frac{V_{cc} - V_{CE\,sat}}{R_L + R_E} R_E + V_{drop}} \approx 5.7V$

~~amplifier~~

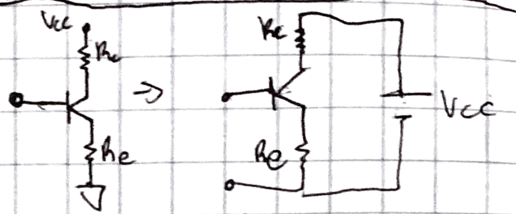
universal DC bias circuit

→ devise a circuit that keeps the transistor operating in the linear active region → sets the constant DC operating conditions | later add AC to produce Amplifier

Vcc ← voltage source



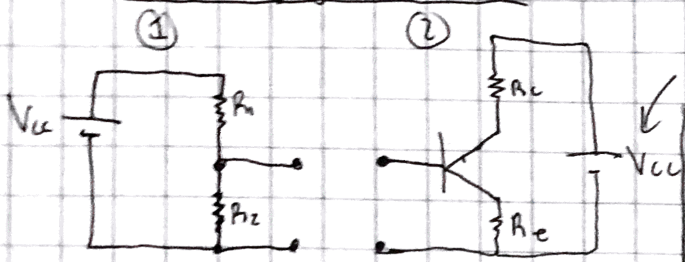
- R_1 and R_2 form a voltage divider
- R_e and R_c complete the circuit
- other bias circuits can be derived from this one



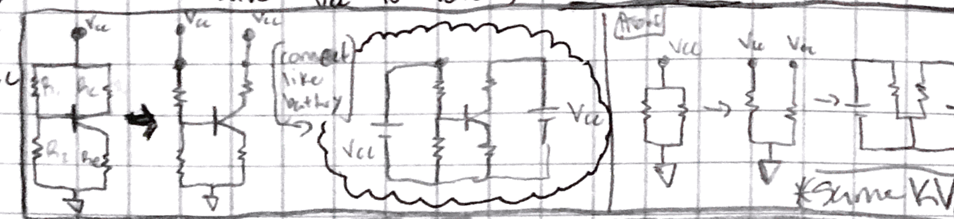
from this thing you can make

this is across Vcc

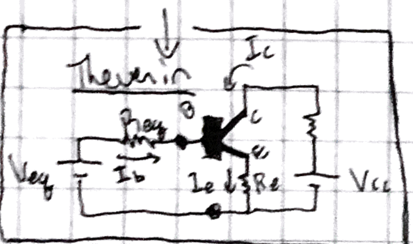
1 2



• also Vcc is across both parts



*same KVL



where:

$$V_{eq} = V_{cc}\left(\frac{R_2}{R_1+R_2}\right), \quad R_{eq} = \frac{R_1 R_2}{R_1+R_2}$$

KVL $V_{eq} - I_b R_{eq} - V_{BE} - I_e R_e = 0$

(voltage drop entire transistor) (voltage drop across diode)

$$V_{cc} - I_c R_c - V_{ce} - I_e R_e = 0$$

~~Using these equations~~ along with, $I_e = I_c + I_b$, $I_c = \beta I_b$ to get * I_e, I_b, V_{ce} *, operating point

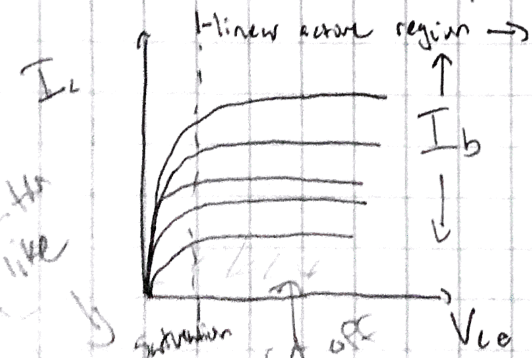
$\boxed{1}$ $I_b = \dfrac{V_{eq} - V_{be}}{R_{eq} + (\beta+1)R_e}$ $\xrightarrow{\text{plugging in } V_{eq},\ R_{eq}}$ $\boxed{I_b\left[\dfrac{R_1R_2}{R_1+R_2} + (\beta+1)R_e\right] = \left(\dfrac{R_2}{R_1+R_2}\right)V_{cc} - V_{be}}$

$\boxed{2}$ $V_{ce} = V_{cc} - I_c\left(R_c + \dfrac{\beta+1}{\beta}R_e\right)$ $\xrightarrow{\text{rearrange}}$ $\boxed{R_c + \left(\dfrac{\beta+1}{\beta}\right)R_e = \dfrac{V_{cc} - V_{ce}}{I_c}}$

*operating point is the DC voltage or current at a specific terminal of an active * device with no input signal applied *

Side note: if input (V_b) varies from 0-1V you could configure transistor to multiply by 5 so it (V_{CE}) goes from 0-5V, If you want to do 1000 but your supply (V_{cc}) is only 5 then it will only go between 0 and 5V

The above circuit keeps transistor in linear active region, its DC mode.



Biasing is the process of providing DC voltage which helps in the functioning of the circuit, A transistor is biased in order to make the emitter-base junction forward biased and the collector-base junction reverse biased, so it remains in linear active region (to work as an amplifier)

(by connecting to a Vcc you can amplify base or input stuff)

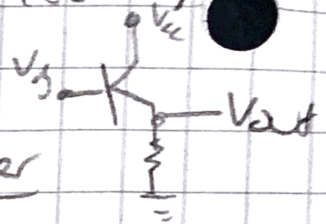
→ Vcc dumps all to E, low base current

6

Tips tricks overview

(open circuit)

- if V_{in} or $V_B < (V_{BE} = V_{drop})$ then there is no flow / cut off



- $V_{CE} > V_{CE_{sat}}$ to be in linear active region

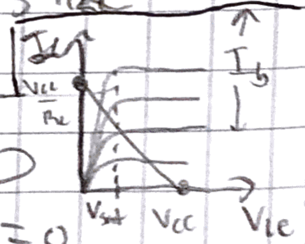
↳ commonly use: $V_{cc} = V_{CE} + V_{out}$, V_{out} is voltage across emitter

↳ you then can use $I_c = \beta I_B \rightarrow I_c \approx I_E$ vs $I_E = \frac{\beta+1}{\beta} I_c$

• β is big

- if $V_{CE} < V_{CE_{sat}}$ you are in saturation $V_{CE_{sat}}$ is small so its like (acts like wire) ($I_c = I_E$)

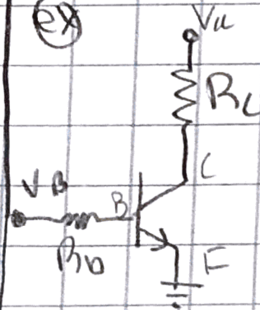
↳ $V_{CE} = 0$



~ impedance seen by V_B is $Z_B = \frac{V_B}{I_B}$

↳ if in linear active

ex



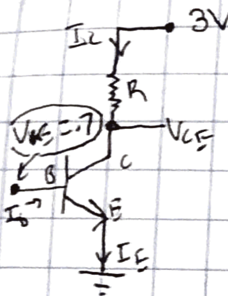
• $V_B = 0$ then $I_b = 0$ which means $I_c = 0$ then $V_{CE} = V_{cc}$ (cut off)

• V_B = big, I_b = big (only if R_B is chosen correctly) then I_c = big and V_{CE} = small (saturation) amplifiers | npn emitter follower can't sink current | pnp follower can't source current

7

Intro

cut off state: (OFF STATE)



① if $V_{BE} < .7V$ (P region isn't biased enough so no flow) (max voltage ever)

$I_b \simeq I_c = 0$ * no voltage drop across R ($V_{CE} = V_{cc} = 3$)

② $V_{BE} \simeq .7V$ lets say $I_b = 10\mu A$ (input current), $\beta = 100$, $R = 1k\Omega$

• $I_c = \beta I_b = 1mA$ and $I_c R = 1V$

↳ so $3V - 1V = V_{CE} = 2V$ (output) * AMPLIFYER *

output across $V_{CE} = 2V$, 1mA

input = $10\mu A$, ~~.7V~~ I think V_{BE} is increasing so I_b increases

↳ $I_b = 30\mu A$ → $\boxed{I_c = 3mA}$ ∴ $I_c R = 3V$ so $V_{CE} = 0$

* max current can't go past 3V drop *

[$0 < I_B < 30\mu A$ → $I_c = \beta I_B$ and $0 < V_{CE} < 3V$]

LINEAR ACTIVE REGION

[$I_B > 30\mu A$ → $I_c = 3mA$ (maximum) $V_{CE} = 0$ min]

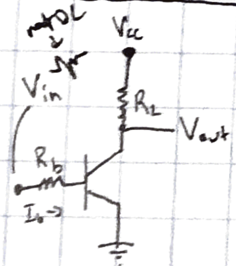
Saturation State (ON STATE)

* Saturation it's fully conducting
↳ acts like wire

* cut off not conducting
↳ acts like open circuit

Transistor as a Voltage Amplifier

we want: $V_{out} = 10 V_{in}$ but it's also amplifying if $\Delta V_{out} = 10 \Delta V_{in}$, which means a DC offset can amplify



$\Delta V_{out} = 10 \Delta V_{in}$ * assume in active state * $I_c = \beta I_b$

* V_{in} is not DC current so I_c and I_b change in time → $\Delta I_c = \beta \Delta I_b$

↳ $[V_{cc} - V_{out} = I_c R_L]\Delta$ (take Δ of definition) → , $V_{cc} = 0$ → $\boxed{-\Delta V_{out} = R_L \Delta I_c}$

$[V_{in} - V_{BE} = I_B R_b]\Delta$ (V_{BE} constant) → $\boxed{\Delta V_{in} = \Delta I_B R_b}$

then: $\boxed{\dfrac{\Delta V_{out}}{\Delta V_{in}} = -\dfrac{R_L}{R_b}\dfrac{\Delta I_c}{\Delta I_b} = -\dfrac{R_L}{R_b}\beta}$

$-\dfrac{R_L}{R_b}\beta$ } → Voltage gain

minus sign just flips magnitude
increase V_{in},

$I_b = \uparrow$ then $I_c = \uparrow$ (more drop across R_L) then $V_{out} \downarrow$

ex