Field Effect Transistors (Schockley, 1952)

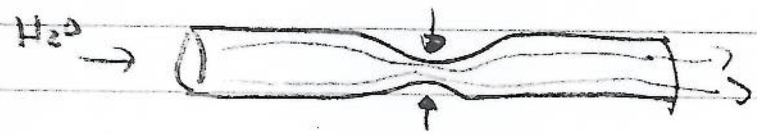
Voltage variable resistors

First half of story:

Consider water hose

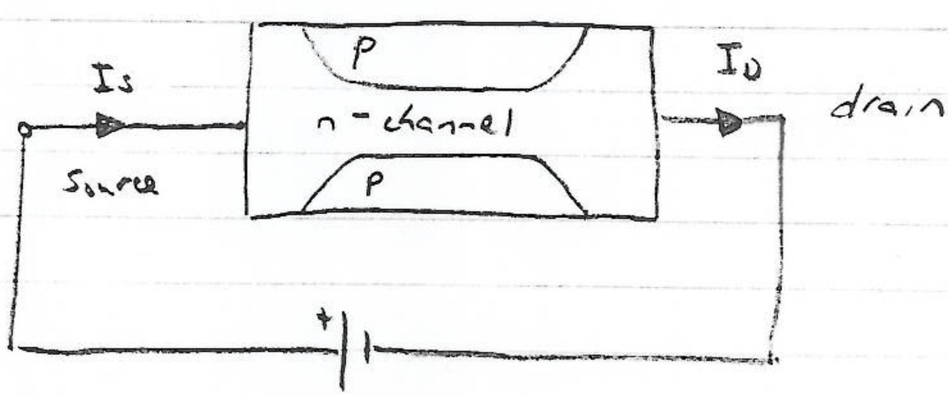
Some impedance to flow

Now pinch it



increased impedance

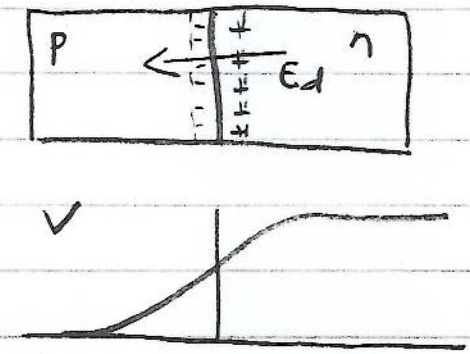
Consider



n doped material makes channel.

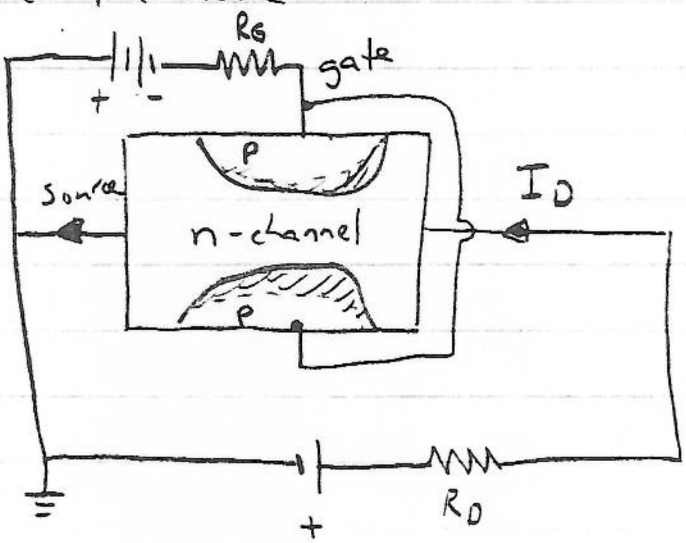
why?

Recall, again n-p junction

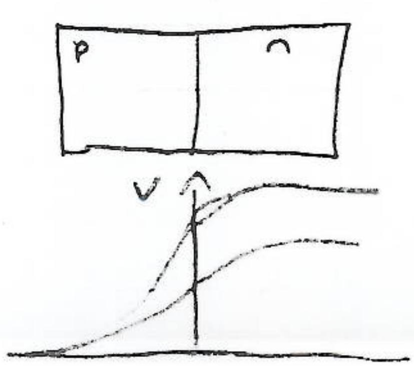


Electric field sweeps away carriers → depletion region
→ insulating

Now, pinch the hose



Reverse biasing p-n junctions

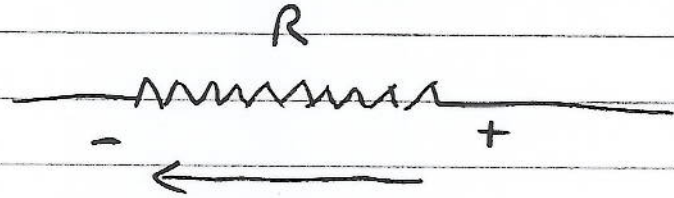


depletion region increases at expense of n-channel

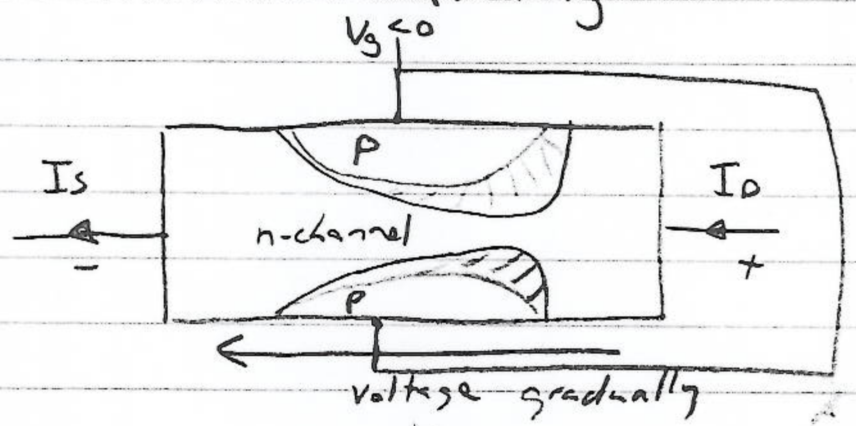
$r = \rho \frac{l}{A}$ smaller A, bigger r

Second half of story

n channel like a (voltage variable) resistor

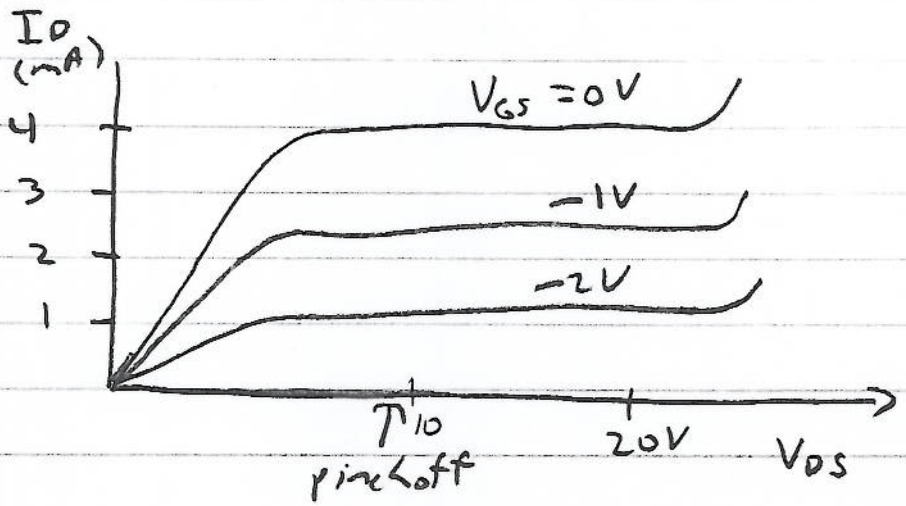


Voltage gradually drops along R

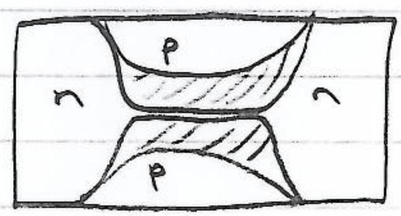


voltage gradually drops

This effect gives $R_{SD} = f(V_{DS})$ - non Ohmic

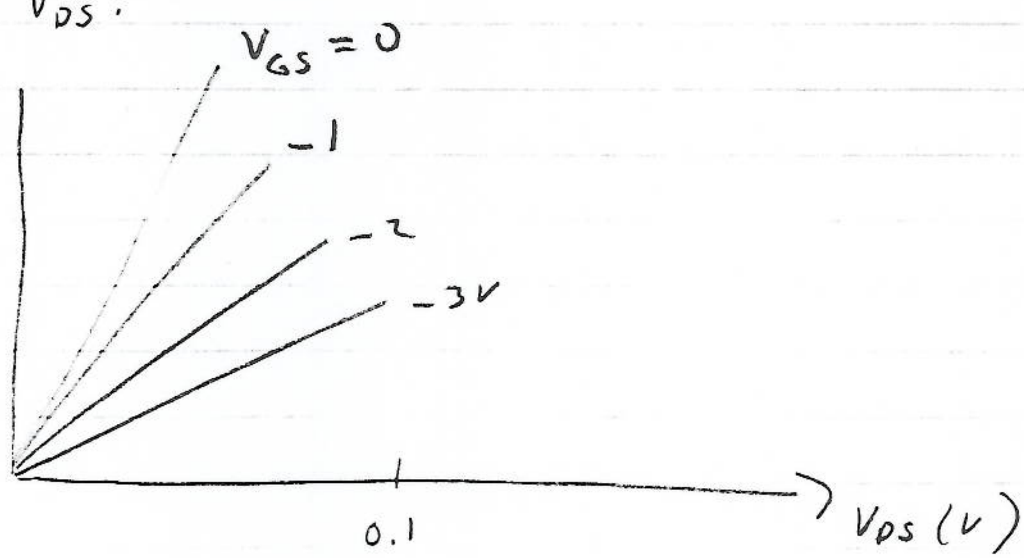


For V_{GS} large enough



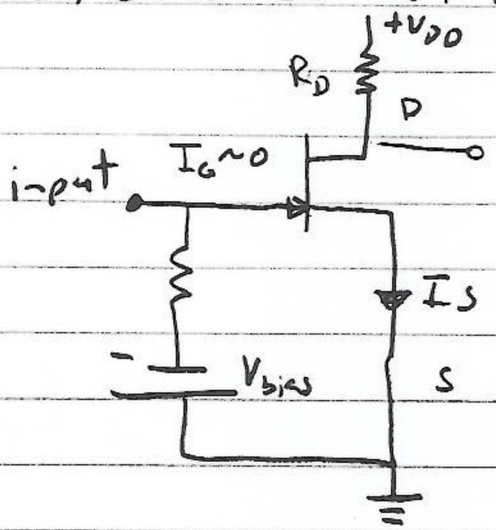
pinchoff → no conduction from drain to source
→ pinchoff

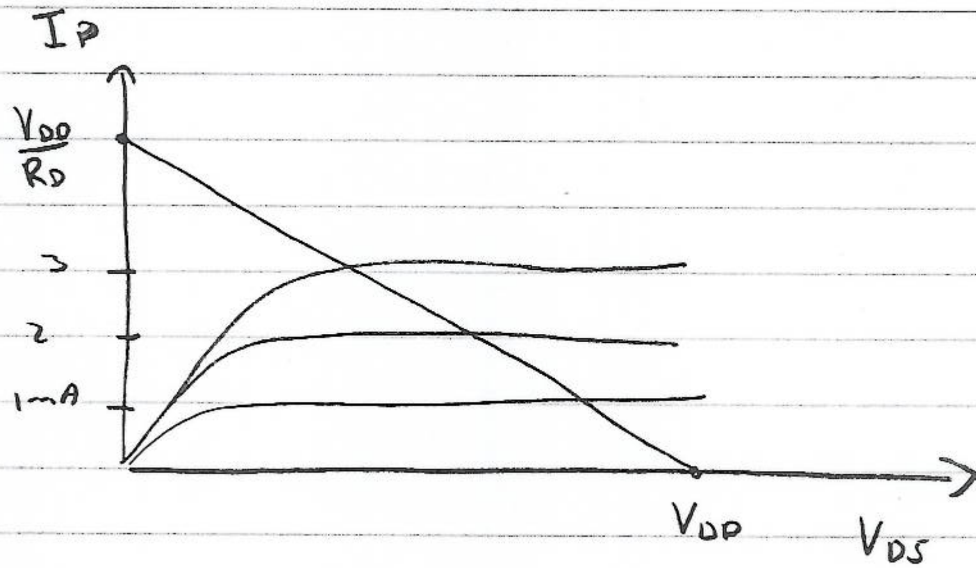
Low V_{DS}:



Linear, variable resistance
VCR - voltage controlled resistance

Common source FET Amplifier - like common emitter





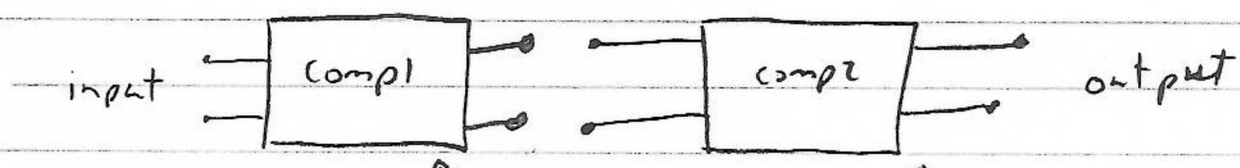
$V_{DD} - I_D R_D - V_{DS} = 0$

$$I_D = \frac{V_{DD}}{R_D} - \frac{V_{DS}}{R_D}$$

Nice thing about FET amps:
gate - source is reverse biased
→ high R btwn them

So what?
In general, want components to have
1) Large input Z
2) small output Z

Often string together components

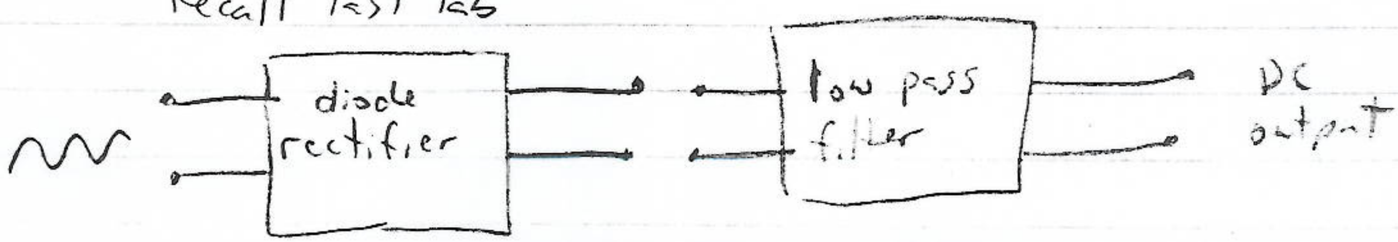


Design this so it does it's job well no matter what this does (within ranges)

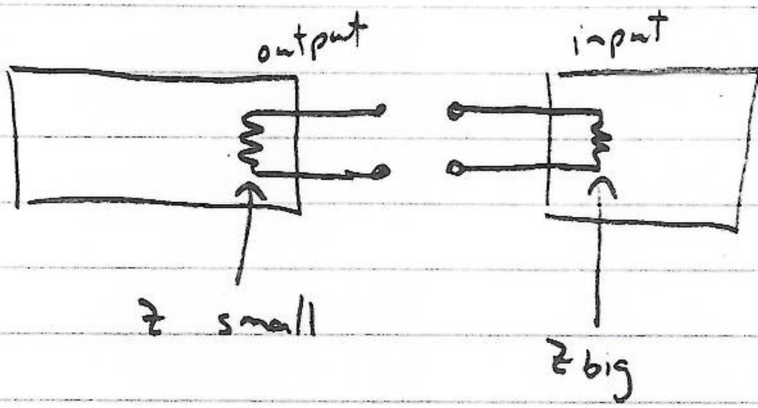
equivalently

Design comp2 so it doesn't load comp1

Recall last lab

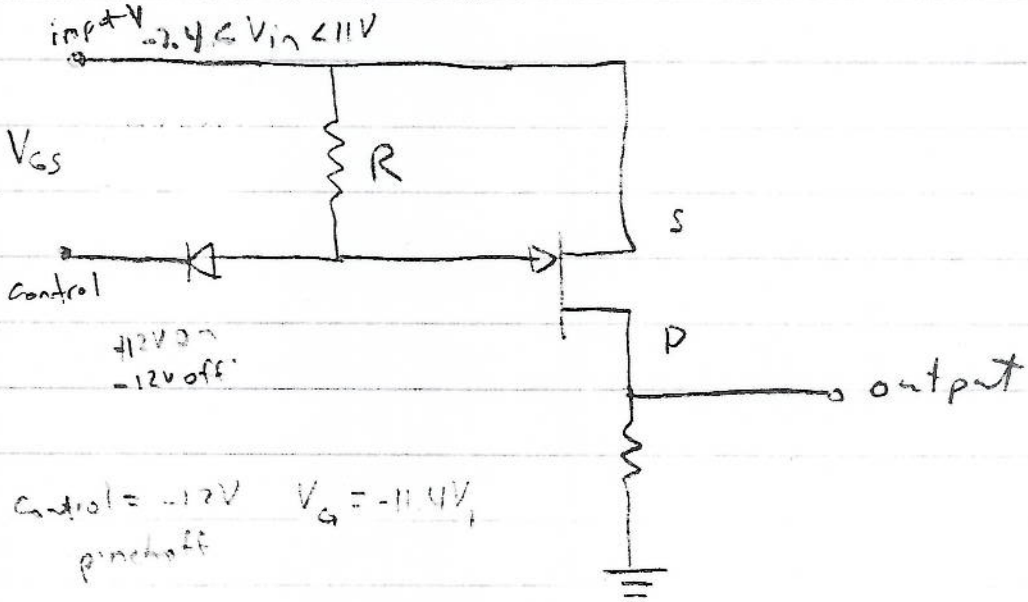


Want

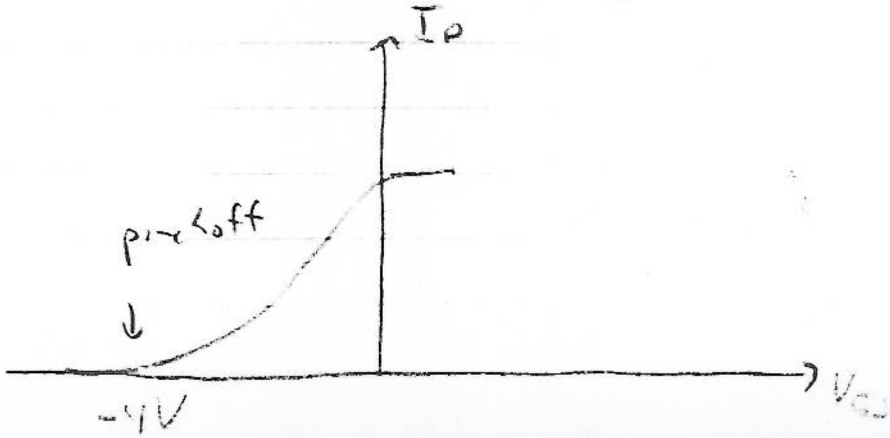


FETs have large Z_{input}.

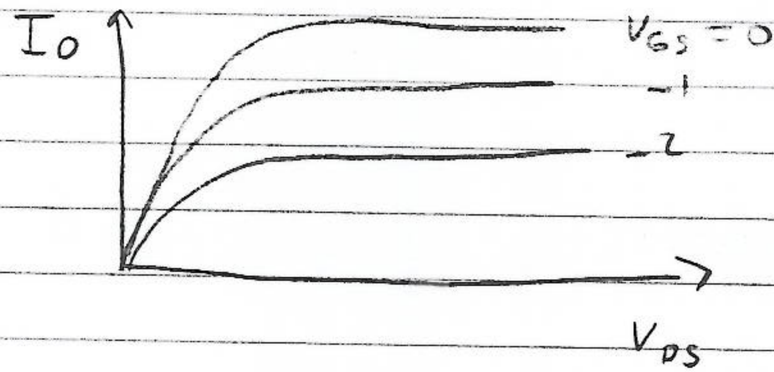
FET switch



Control = -12V V_G = -11.4V,
pinchoff



FET constant current source

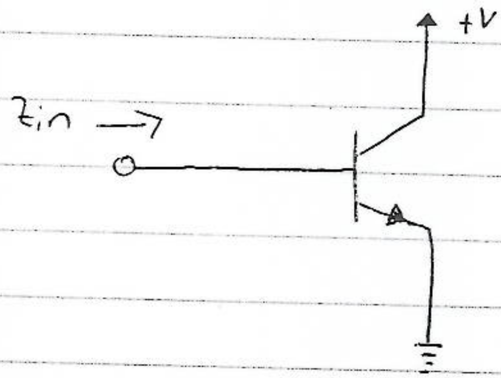


Input Impedence to a transistor (BJT) base

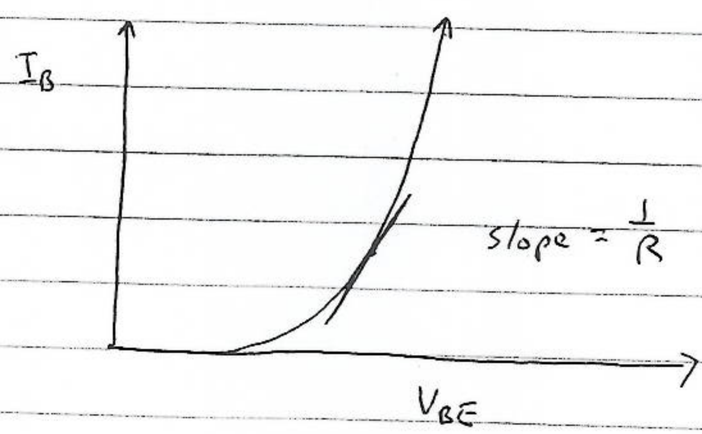
Interested in A.C. impedence

$$Z_{AC} = \partial V / \partial I$$

First, look at grounded emitter



Recall Base - emitter characteristic

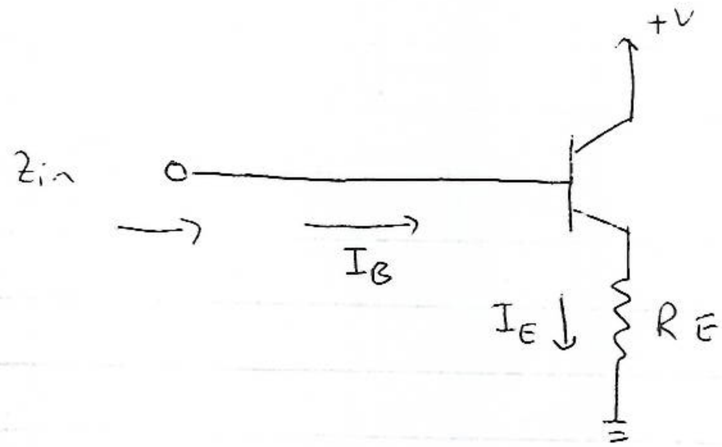


Impedence, h_{ie}, depends where transistor is biased

$\sim 1 k\Omega$

Less at higher bias currents

Now consider



If we put I_B into base
$I_E = \beta I_B$ flows into emitter lead through emitter resistance

V_E goes up by $I_E R_E = \beta I_B R_E$

Since V_{BE} = const V_B goes up w/ V_E

$$Z_{\substack{\text{into}\\\text{base}\\\text{from } R_E}} = \frac{\partial V_B}{\partial I_B} = \frac{\beta I_B R_E}{I_B} = \beta R_E$$

Total $Z_{\substack{\text{into}\\\text{base}}}$

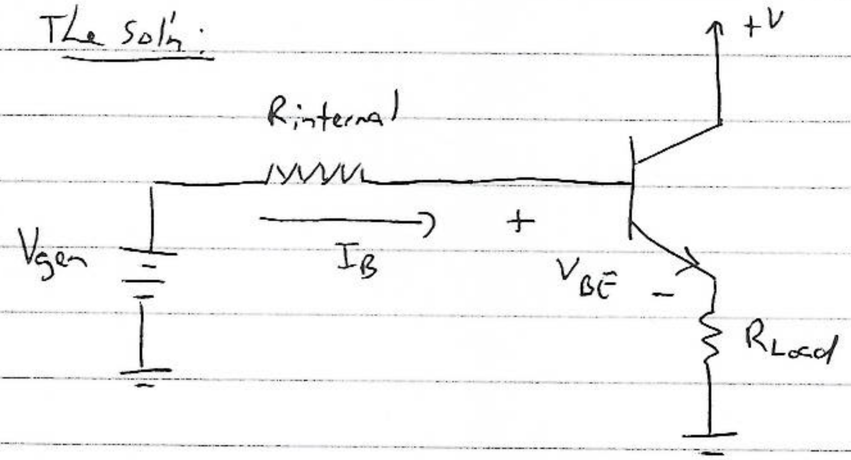
$$\boxed{Z_{\substack{\text{into}\\\text{base}}} = h_{ie} + \beta R_E}$$

This is basis for "emitter follower"
or "buffer circuit"

The problem

Suppose we have voltage generator w/ high internal impedance which we want to use to drive a low impedance load.

The sol'n:



Z_{in} made large even though R_{load} may be small, by β of transistor

Disadvantages

(1) nearly constant offset V_{BE}.
No biggie if $V_{gen} > V_{BE}$
(2) Only works for V_{gen} +.

Feedback

Take some fraction of output → send it back to input

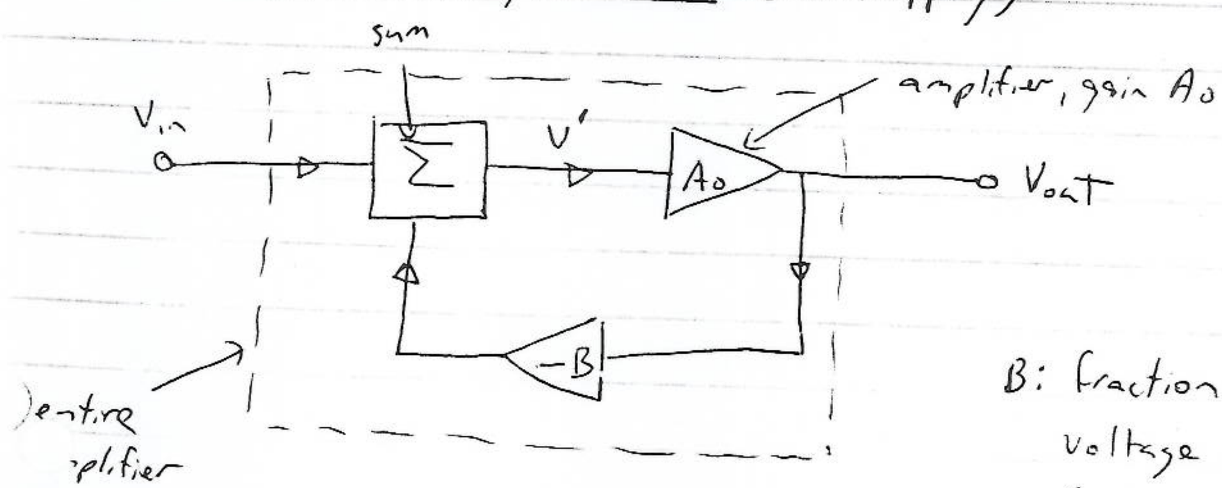
In phase, positive feedback

- increase gain
- generate constant or repetitive output

Out of phase, negative feedback

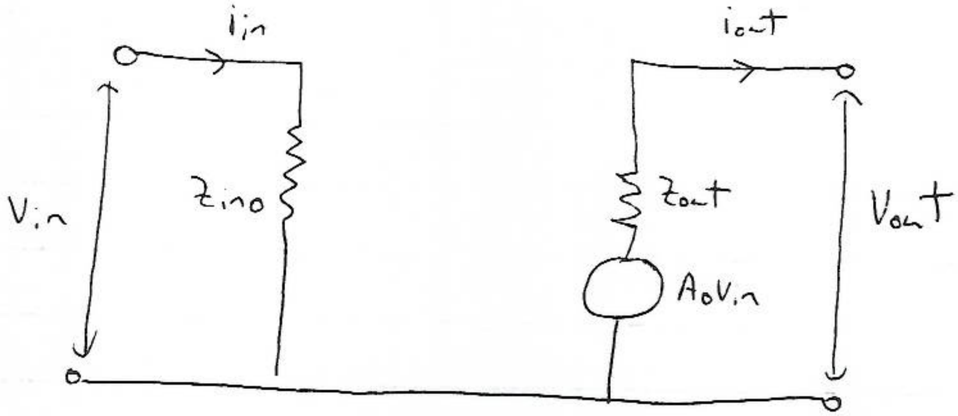
- increase circuit stability
  - temperature
  - power supply voltage fluctuations
  - radiation damage, aging of transistors
- increased input impedence
- decreased output impedence
- decreased distortion
- increased bandwidth

Negative Voltage Feedback (bootstrapping)

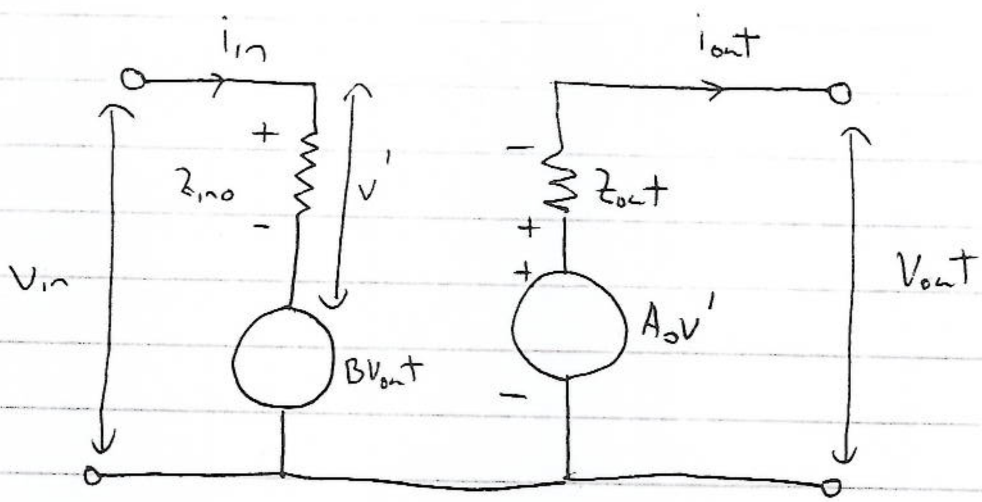


B: fraction of output voltage subtracted from input; feedback factor

$$V' = V_{in} - BV_{out}$$



no feedback



$$V' = V_{in} - BV_{out}$$

With feedback

$$V_{in} = V' + BV_{out}$$

$$V' = i_{in} Z_{in0}$$

$$\left(A_f = \frac{V_{out}}{V_{in}} = \frac{A_0}{1 + A_0 B} \right)$$

$A_o = \frac{V_{out}}{V'}$ open loop gain

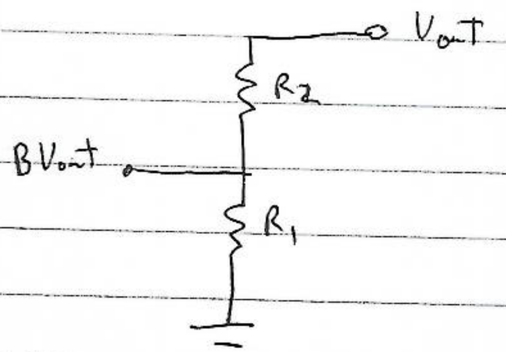
$$A_f = \frac{V_{out}}{V_{in}}$$

$$A_f = \frac{A_o V'}{V' + B V_{out}} = \frac{A_o V'}{V' + B A_o V'} = \frac{A^o}{1 + B A_o}$$ smaller than A^o

Nice thing #1:

If $A_o B$ large $A_f = \frac{1}{B}$ depends only on B, <u>not</u> A_o

B easy to make constant



$$B = \frac{R_1}{R_1 + R_2}$$

$$A_f = \frac{R_1 + R_2}{R_1} = 1 + \frac{R_2}{R_1}$$

Nice thing #2:

Increase input impedence

→ net effective input voltage reduced, smaller current

$$Z_{inf} = \frac{V_{in}}{i_{in}} = \frac{V' + BV_{out}}{i_{in}} = \frac{i_{in}Z_{ino} + BV_{out}}{i_{in}}$$

$$V_{in} = i_{in}Z_{ino} + BV_{out}$$

$$V_{out} = V_{in}\frac{A_0}{1+A_0B}$$

$$V_{in} = i_{in}Z_{ino} + B\,V_{in}\frac{A_0}{1+A_0B}$$

$$Z_{inf} = \frac{V_{in}}{i_{in}} \qquad V_{in}\left(1 - \frac{A_0B}{1+A_0B}\right) = i_{in}Z_{ino}$$

$$Z_{inf} = \frac{Z_{ino}}{1 - \frac{A_0B}{1+A_0B}} = Z_{ino}\underbrace{(1+A_0B)}_{>1}$$

(nice thing #2)

Nice thing #3:

Decrease output impedence

Again, $V' = V_{in} - BV_{out}$

$$V_{out} = A_0V' - i_{out}Z_{out}$$

$$Z_{outf} = -\frac{\partial V_{out}}{\partial i_{out}}$$

Eliminate v'

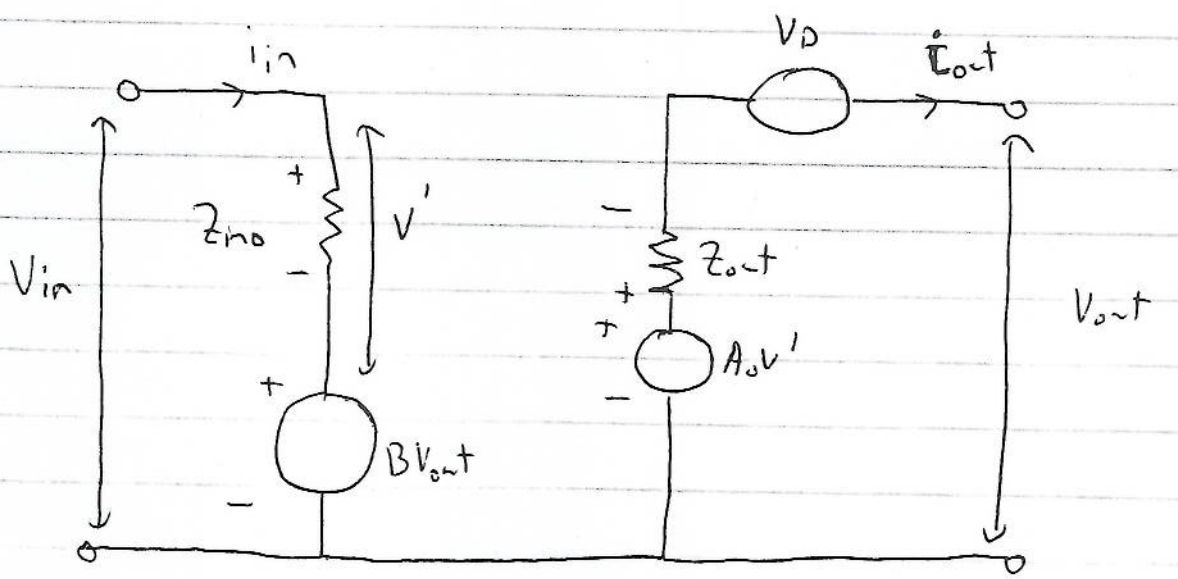
$$V_{out} = A_o(V_{in} - B V_{out}) - i_{out} Z_{out}$$

$$V_{out} = \frac{A_o V_{in} - i_{out} Z_{out}}{1 + A_o B}$$

$$Z_{out_f} = \frac{Z_{out}}{1 + A_o B}$$

$\underset{\text{w/ feedback}}{Z_{outf}} < \underset{\text{w/o feedback}}{Z_{out}}$ (Nice thing #3)

Nice thing #4
Decrease of distortion



$$V_{out} = A_o v' - i_{out} Z_{out} + V_D$$

$$V_{in} = v' + B V_{out}$$

Eliminate v'

$$V_{out} = A_o \left(V_{in} - B V_{out} \right) - i_{out} Z_{out} + V_D$$

If i_{out} is small

$$V_{out} = A_o \left(V_{in} - B V_{out} \right) + V_D$$

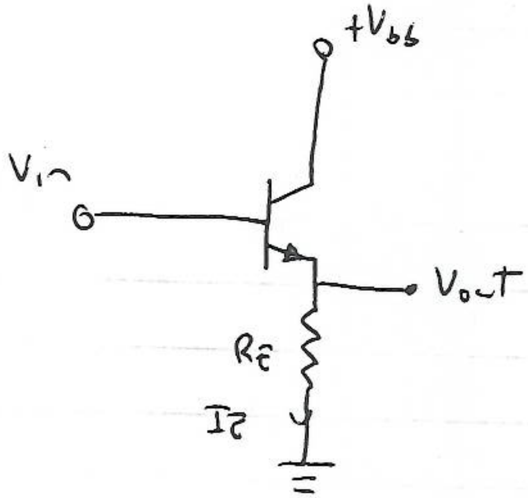
$$V_{out} \left(1 + A_o B \right) = A_o V_{in} + V_D$$

$$V_{out} = \frac{A_o}{1 + A_o B} V_{in} + \frac{1}{1 + A_o B} V_D$$

(Nice thing #4)

Gain for V_{in} <u>bigger than</u> Gain for V_D

Emitter follower :



$$V_{in} = V_{BE} + I_E R_E$$

$$V_{out} = I_E R_E$$

$$V_{in} = V_{BE} + V_{out}$$

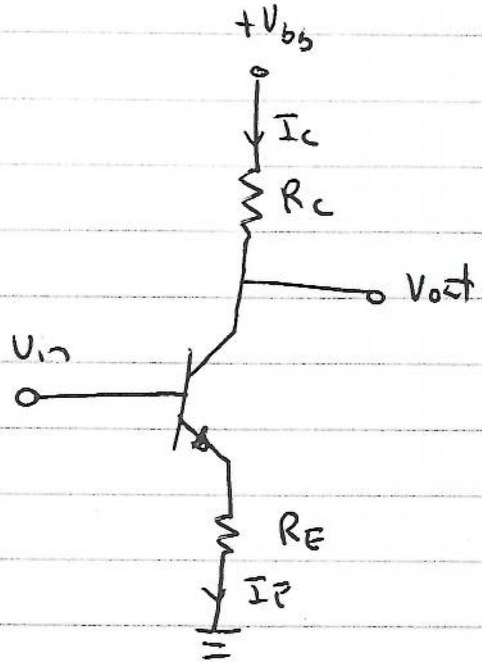
$$V_{BE} = V_{in} - V_{out}$$

Like negative voltage feedback

$$V' = V_{in} - B V_{out} \qquad w/\ B = 1$$

$$A_f \approx \frac{1}{B} = 1$$

Common emitter



A.C. values

$V_{in} = V_{BE} + I_E R_E$ $\quad$ $V_{out} = -I_C R_C$

When $V_{in} \to +$

I_E increases

$V_E \to +$

$V_{BE} < V_{in}$

$\to$ Negative feed back

$$I_C = \beta I_B$$
$$I_C + I_B = I_E$$

$$I_c + \frac{1}{\beta} I_c = I_E$$

$$I_c\left(1 + \frac{1}{\beta}\right) = I_E$$

$$I_c = \frac{\beta I_E}{\beta+1}$$

So,

$$V_{in} = V_{BE} + R_E \frac{\beta+1}{\beta} I_c$$

$$= V_{BE} - R_E \frac{\beta+1}{\beta R_E} V_{out}$$

$$V_{BE} = V_{in} + \frac{\beta+1}{\beta} \frac{R_E}{R_c} V_{out}$$

$$v' \to V_{BE}$$

$$v' = V_{in} - B\, V_{out}$$

$$B = -\frac{\beta+1}{\beta} \frac{R_E}{R_c}$$

$$A_f \cong \frac{1}{B} = \frac{-\beta R_c}{(\beta+1)R_E} \approx -\frac{R_c}{R_E}$$

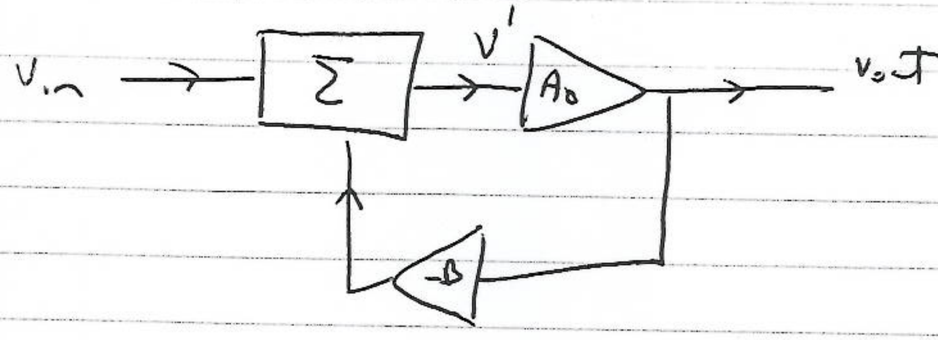
$\uparrow$

180^0 phase inversion

Negative current Feedback

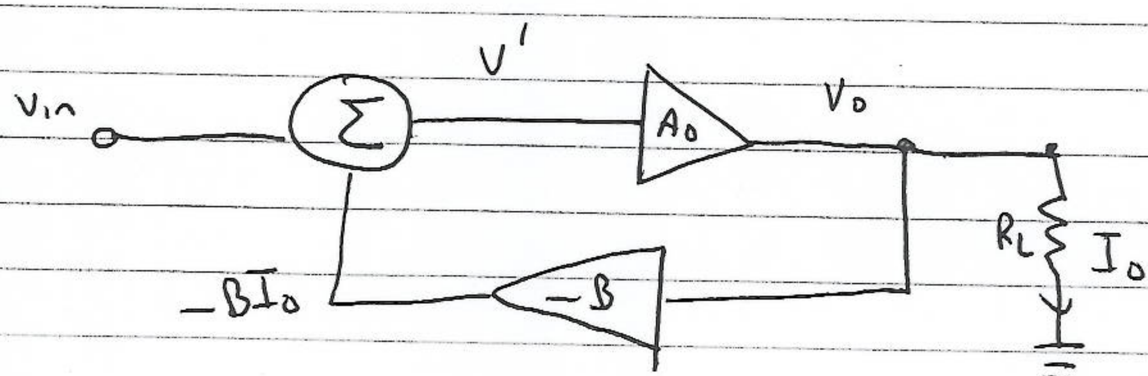
$\rightarrow$ Constant current source

Remember



$\uparrow$ fraction of voltage feedback

Now consider



$V' = V_{in} - B I_0$

voltage feedback $= BI_0$

$V_0 = I_0 R_L = A_0 V'$

3

$$I_o R_L = A_o(V_{in} - B I_o)$$

$$I_o(R_L + A_o B) = A_o V_{in}$$

$$I_o = \frac{A_o V_{in}}{R_L + A_o B}$$

If $A_o B >> R_L$

$$I_o \approx \frac{V_{in}}{B} \qquad \frac{I_o}{V_{in}} = \frac{1}{B}$$

Current output $\propto V_{in}$

$\frac{1}{B}$ → transconductance