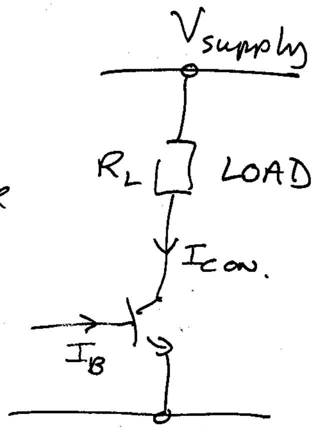
Driving a Bipolar Transistor Switch.



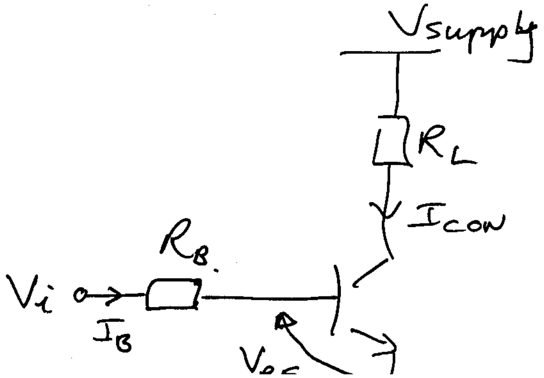
To work out I_{CON} assume that switch has negligible on-state voltage across it.

$$I_{CON} = \frac{V_{supply}}{R_L}$$

$\frac{I_C}{I_B} \approx$ constant $\Rightarrow h_{FE}$ static current gain.

h_{FE} varies significantly from device to device $\longrightarrow$ manufacturers specify a MIN + MAX + sometimes typical value.

We <u>must</u> use the $h_{FE\,MIN}$ if we want all specimens of this transistor type to switch properly.



$$I_B = \frac{V_{i\,ON} - V_{BE\,ON}}{R_B}$$

I must use $I_{B\,MAX}$ here — $I_{B\,MAX}$ comes from using $h_{FE\,MIN}$.

$$I_{B\,MAX} = \frac{I_{CON}}{h_{FE\,MIN}}$$

$$\therefore \frac{I_{CON}}{h_{FE\,MIN}} = \frac{V_{i\,ON} - V_{BE\,ON}}{R_B}.$$

$$\text{or} \quad R_B = \frac{(V_{i\,ON} - V_{BE\,ON})\,h_{FE\,MIN}}{I_{CON}}.$$

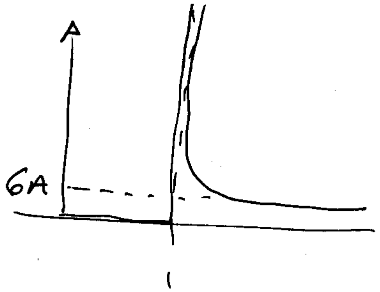
What if the load is something a bit more complicated than a simple — eg a car head lamp.

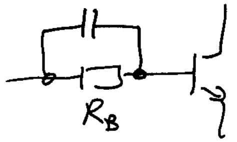
eg 72W lamp from 12V

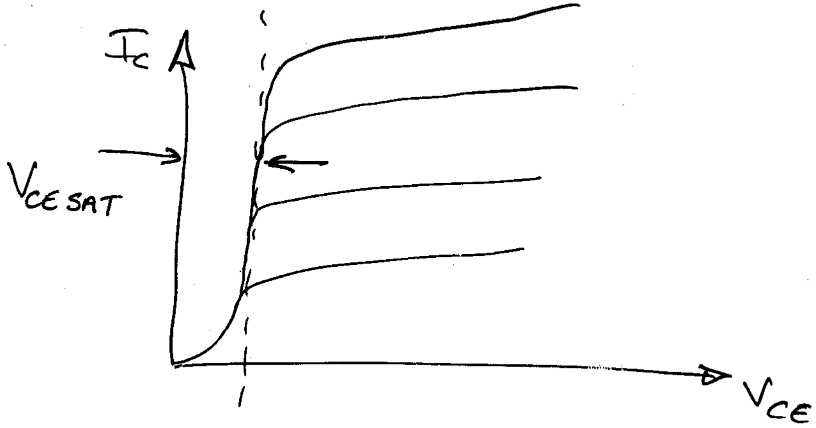
$$P = V^2/R \qquad \frac{144}{72} = 2\,\Omega.$$

hot resistance.

The cold resistance of a lamp like this will typically be around an order of magnitude lower than the hot resistance.







Power dissipated in transistor

is $V_{CESAT} \times I_{CON} \equiv P_D$

How is the transistor chosen

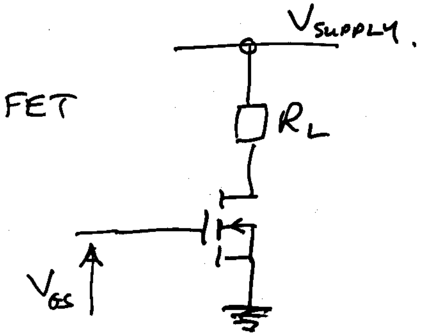
Transistor must be able to

1) withstand the off-state voltage (which usually equals the V_{SUPPLY})
2) withstand the on-state current (usually $I_{con} = \frac{V_{SUPPLY}}{R_L}$)
3) dissipate sufficient thermal energy (ie, P_D)

Need to look for maximum ratings that are bigger than 1, 2 + 3.

MOSFET SWITCHES.

To switch the MOSFET "on" – a V_{GS} of between 10 + 15V is needed.



On state current → $\frac{V_{SUPPLY}}{R_L} = I_{DON}$

In the "on" state the MOSFET behaves like a resistance, r_{DSON}

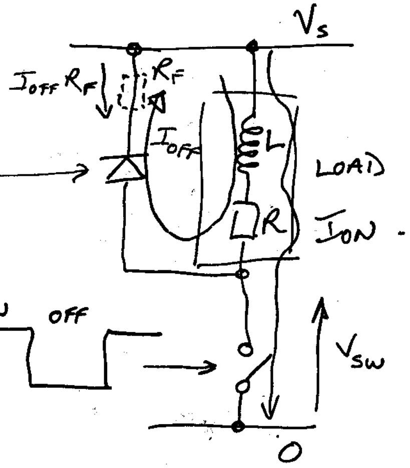
So on-state power loss $= I_{DON}^2 \cdot r_{DSON}$.

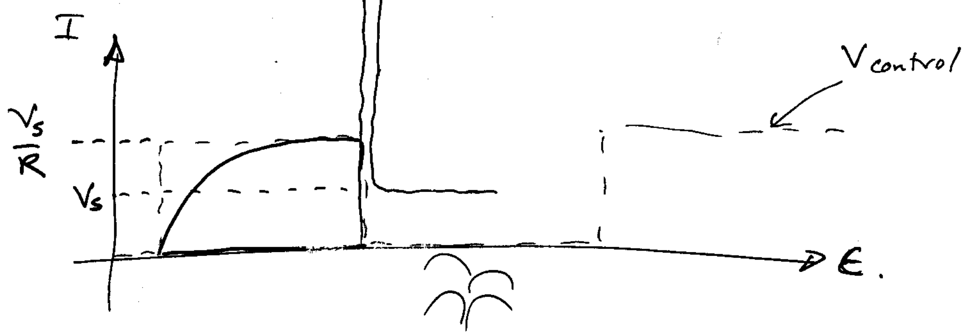
Switches with inductive loads

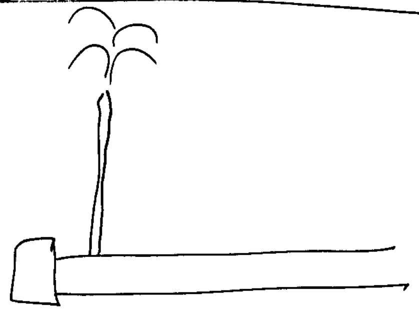
Its all about $V = L\frac{dI}{dt}$.

Driver for I_{OFF} is the inductor.

"idling" or "freewheeling" diode





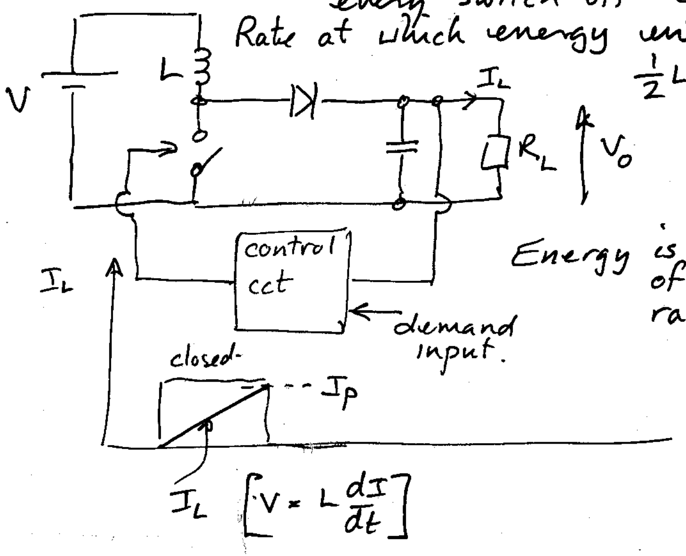


Energy entering C = $\frac{1}{2}LI_p^2$ every switch off event.
Rate at which energy enters C is

Energy entering C = $\frac{1}{2}LI_p^2$ every switch off event.

Rate at which energy enters C is $\frac{1}{2}LI_p^2 \times f_s$

switching frequency.



Energy is drawn out of C at a rate of $I_L V_o$ W

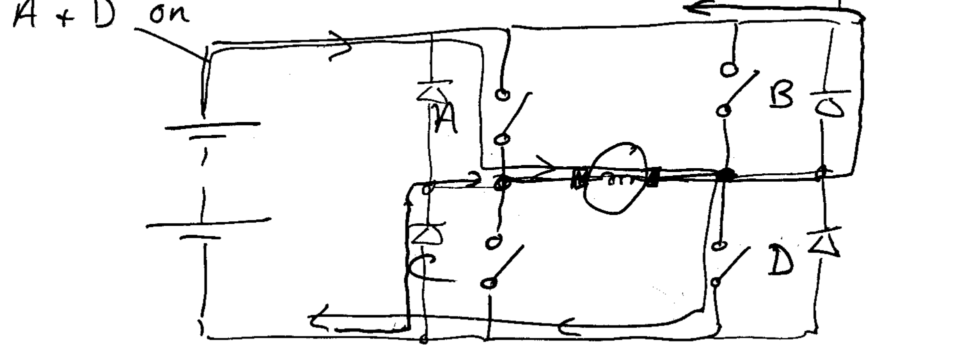
$W = J\,s^{-1}$

Full Switch Bridge Circuit

— used in motor control (ac or dc)

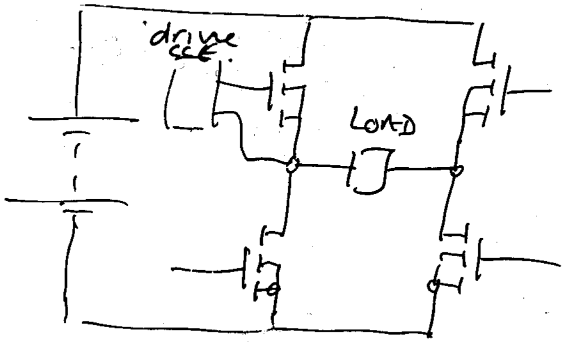
A + D "on"

turn off idling current



if switch A + D are "on", current will flow from left to right

if switch C + B are "on", current will flow from right to left.



Bipolar v Mosfets.

Bipolar:

low on-state voltage drop

medium speed — works up to ~ 100 kHz

relatively high control cct power.

Mosfets:

higher on state voltage drop

fast – will work up to MHz

easy to control

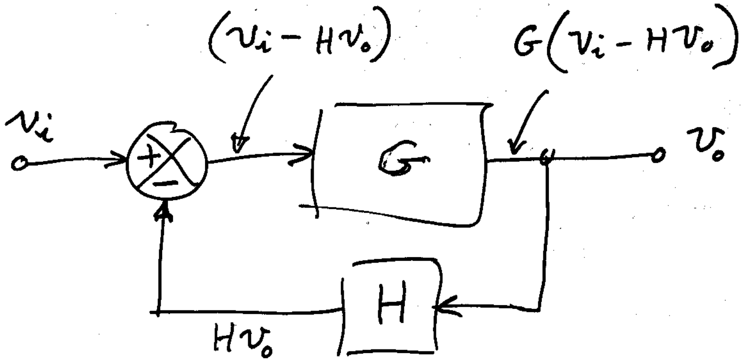
don't need much control power.

Insulated Gate Bipolar Transistor

— hybrid BJT/MOSFET

Operational Amplifiers

$(v_i - Hv_o)$ $G(v_i - Hv_o)$



So $G(v_i - Hv_o)$ must equal v_o

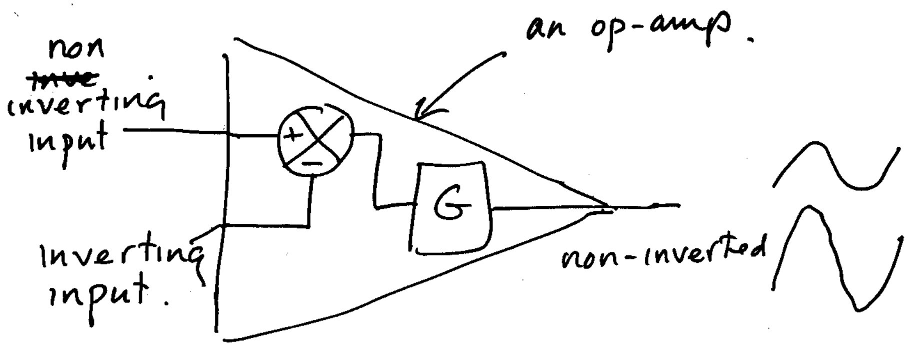
rearranging to get $\frac{v_o}{v_i}$ = system gain

$$= \frac{G}{1+GH}$$

if G can be made sufficiently big such that $GH \gg 1$

$$\frac{v_o}{v_i} \approx \frac{G}{GH} = \frac{1}{H}$$

So what is inside a normal op-amp



G typically 10^4 to 10^7 V/V.

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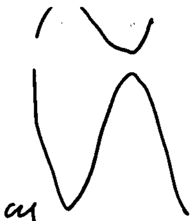
wide frequency range —say 100s MHz

low frequency up to a couple of MHz.

inverted



The key equation for op-amps

$$v_o = A_v\left(v^+ - v^-\right)$$

A_v: open loop gain (G in the classic control system)

v^+: non-inverting input voltage

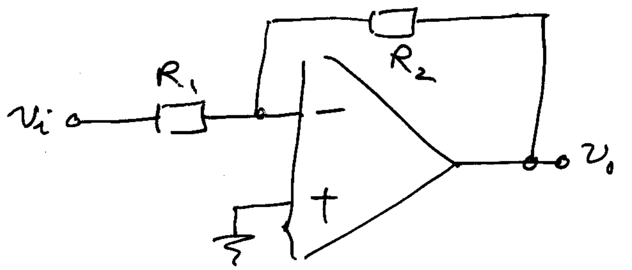
v^-: inverting input voltage

if $A_v \Rightarrow \infty$ then for finite v_o

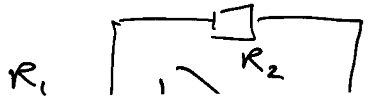
$(v^+ - v^-) \Rightarrow 0$

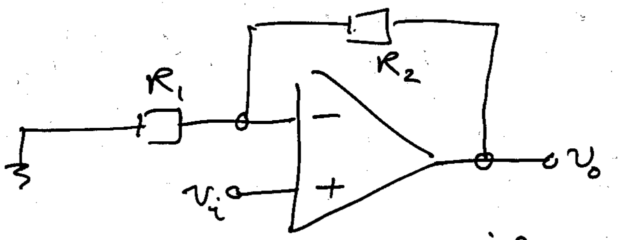
so $v^+ \approx v^-$

Two basic circuit shapes



inverting amplifier.

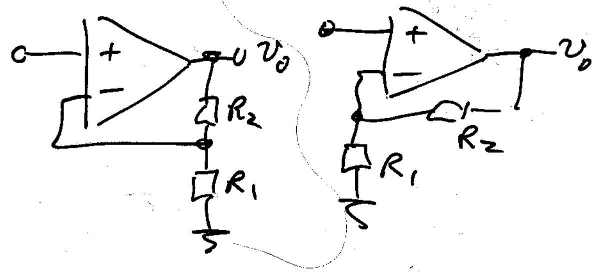




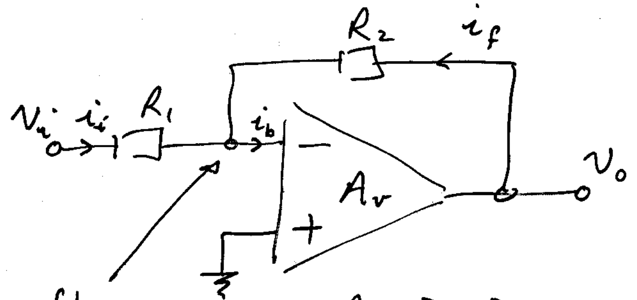
non-inverting amplifier

Note the similarities between these two circuits.

other common forms of non-inverting



<u>Designing an inverting amplifier</u>



often called a "virtual ground" or "virtual earth"

$A_v \Rightarrow \infty$

$v_o = A_v(v^+ - v^-)$

$\therefore\ v^+ - v^- \Rightarrow 0$ for a finite v_o

i_b is usually negligibly small.

Summing currents at v^- node

$$i_i + i_f = 0$$

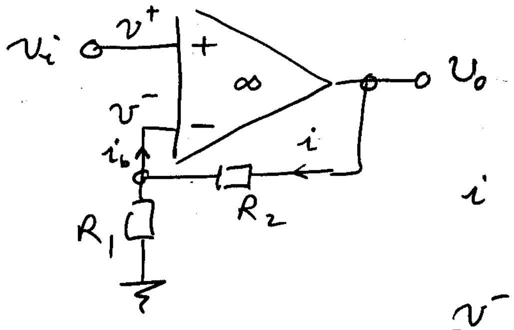
$$\frac{v_i - 0}{R_1} + \frac{v_o - 0}{R_2} = 0 \quad \text{or} \quad \frac{v_i}{R_1} = -\frac{v_o}{R_2}$$

$$\text{or} \quad \frac{v_o}{v_i} = \text{gain} = -\frac{R_2}{R_1}$$

Non-inverting amplifier

– again assume $A_v \Rightarrow \infty$

so $v^+ \approx v^-$



$$i = \frac{v_o}{R_1+R_2}$$

i_b negligibly small

$$v^- = iR_1 = \frac{v_o R_1}{R_1+R_2}$$

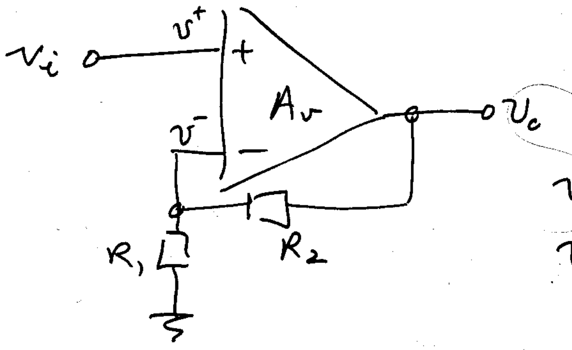
$$v^+ = v^-$$

$$v_i = \frac{v_o R_1}{R_1+R_2}$$

$$\frac{v_o}{v_i} = \frac{R_1+R_2}{R_1}$$

What is the effect of A being finite

Non inverting with finite A_v



$$v_i = v^+$$

$$v^- = \frac{v_o R_1}{R_1+R_2}$$

$$v_o = A_v(v^+ - v^-)$$

$$= A_v\left(v_i - \frac{v_o R_1}{R_1+R_2}\right)$$

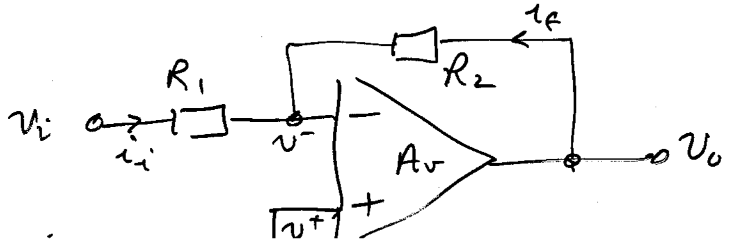
$$v_o\left[\frac{1}{A_v} + \frac{R_1}{R_1+R_2}\right] = v_i$$

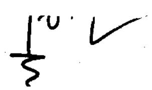
$$\frac{v_o}{v_i} = \frac{1}{\frac{1}{A_v} + \frac{R_1}{R_1+R_2}}$$

for A_v to have a negligible effect on $\frac{v_o}{v_i}$

$$A_v \gg \frac{R_1+R_2}{R_1}$$

~~Re~~ Inverting Amplifier with finite A_v.





sum currents at inverting input node

$$i_i + i_f = 0$$

$$\frac{v_i - v^-}{R_1} + \frac{v_o - v^-}{R_2} = 0$$

$$\frac{v_i}{R_1} + \frac{v_o}{R_2} = v^-\left[\frac{1}{R_1} + \frac{1}{R_2}\right] = v^-\left[\frac{R_1+R_2}{R_1R_2}\right]$$

$$\frac{v_iR_2}{R_1+R_2} + \frac{v_oR_1}{R_1+R_2} = v^-$$

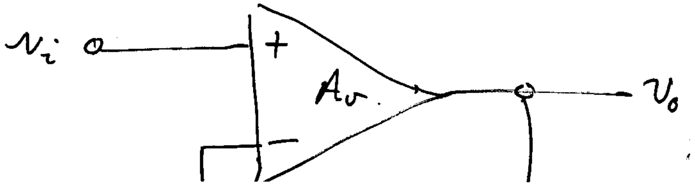
using $v_o = A_v(v^+ - v^-)$

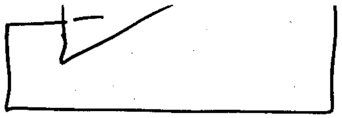
$$\frac{v_o}{A_v} = 0 - \frac{v_iR_2}{R_1+R_2} - \frac{v_oR_1}{R_1+R_2}$$

$$v_o\left[\frac{1}{A_v} + \frac{R_1}{R_1+R_2}\right] = -\frac{v_iR_2}{R_1+R_2}$$

$$\frac{v_o}{v_i} = \frac{-\frac{R_2}{R_1+R_2}}{\frac{1}{A_v} + \frac{R_1}{R_1+R_2}}$$

Unity gain buffer



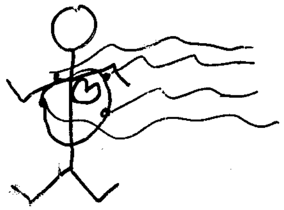


$$v_o = A_v(\underset{v_i}{v^+} - \underset{v_o}{v^-})$$

$$v_o = A_v(v_i - v_o)$$

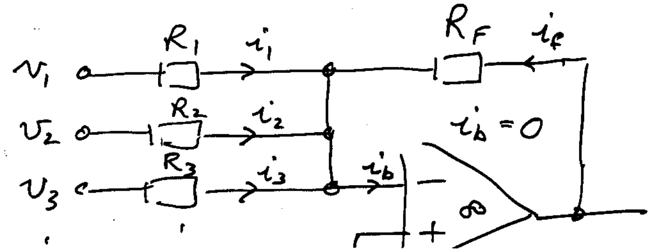
$$v_o(1 + A_v) = A_v v_i$$

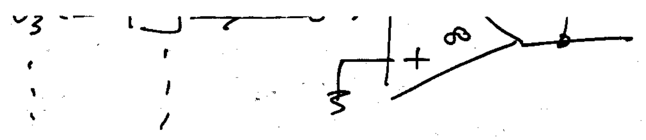
$$\frac{v_o}{v_i} = \frac{A_v}{1+A_v} \approx 1$$



Op-amp circuits with multiple inputs.

i) A summing circuit...





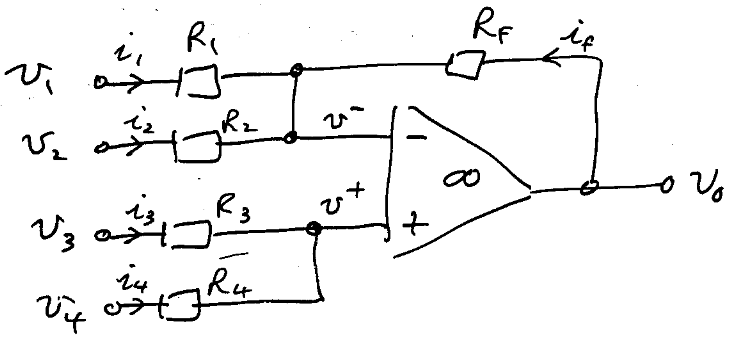
Sum currents at inverting input node

$$i_1 + i_2 + i_3 + i_f = 0$$

$$\frac{v_1 - 0}{R_1} + \frac{v_2 - 0}{R_2} + \frac{v_3 - 0}{R_3} + \frac{v_o - 0}{R_F}$$

or $$v_o = -v_1\frac{R_F}{R_1} - v_2\frac{R_F}{R_2} - v_3\frac{R_F}{R_3} - \dots$$

A more general multiple input problem



Two approaches are useful

1) superposition principle.
2) work out v^+, work out v^- and then equate them.

using method 2 ...
sum currents at v^- node

$$i_1 + i_2 + i_f = 0$$

$$i_1 + i_2 + i_f = 0$$

$$\frac{v_1 - v^-}{R_1} + \frac{v_2 - v^-}{R_2} + \frac{v_o - v^-}{R_F}$$

$$\frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_4}{R_F} = v^-\left[\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_F}\right]$$

or $$v^- = \frac{\frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_o}{R_F}}{\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_F}\right)}$$

summing currents at v^+ node.

$$i_3 + i_4 = 0$$

$$\frac{v_3 - v^+}{R_3} + \frac{v_4 - v^+}{R_4} = 0$$

$$\frac{v_3}{R_3} + \frac{v_4}{R_4} = v^+\left[\frac{1}{R_3} + \frac{1}{R_4}\right].$$

$$v^+ = \frac{\frac{v_3}{R_3} + \frac{v_4}{R_4}}{\frac{1}{R_3} + \frac{1}{R_4}}$$

now equate v^+ and v^-

$$\frac{\frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_o}{R_F}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_F}} = \frac{\frac{v_3}{R_3} + \frac{v_4}{R_4}}{\frac{1}{R_3} + \frac{1}{R_4}}$$

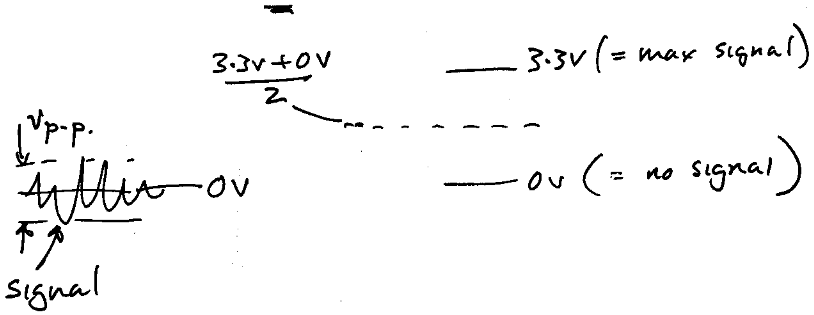
hence

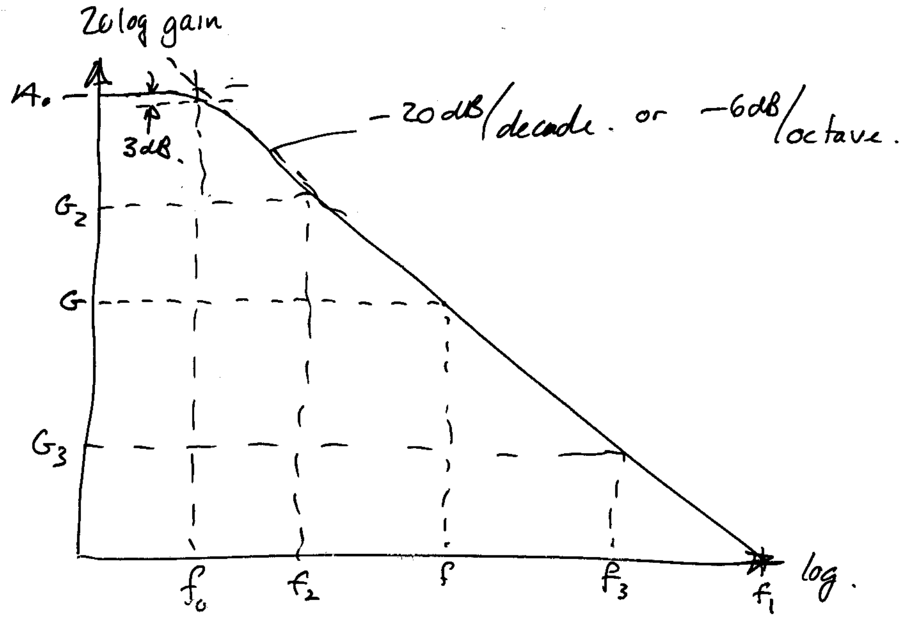
$$\frac{v_o}{R_F} = \frac{\frac{v_3}{R_3} + \frac{v_4}{R_4}}{\frac{1}{R_3} + \frac{1}{R_4}}\left[\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_F}\right] - \frac{v_1}{R_1} - \frac{v_2}{R_2}$$

$$= \frac{\frac{v_3}{R_3} + \frac{v_4}{R_4}}{} \left(\quad '' \quad \right) - '' - ''$$

$$= \frac{\frac{v_3}{R_3} + \frac{v_4}{R_4}}{\frac{R_3+R_4}{R_3R_4}} \left[\quad '' \quad \right] - \,'' - ''$$

$$= \underbrace{\left(\frac{R_4}{R_3+R_4} v_3 + v_4 \frac{R_3}{R_3+R_4} \right)}_{v^+} \left[\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_F} \right] - \frac{v_1}{R_1} - \frac{v_2}{R_2}$$





$G \times f$ = constant

called "gain-bandwidth" product.

$G \times f = G_2 f_2 = G_3 f_3 = 1 \times f_1$

also called "unity gain frequency"