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Advice:

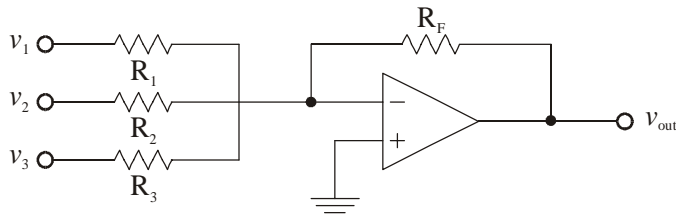
NB: problems 8.12 – 8.13 → supplementary
 Please tell everyone!

Today: **lec 8** OP AMP II
 lec 9 TH Mar 8
 lec 10 TH Mar 15
 lec 11 TH Mar 22

Report solutions posted.

Circuit Analysis

Example 4
 Summer



(-) is grounded ⇒

$$\frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_3}{R_3} + \frac{v_{out}}{R_F} = 0$$

$$R_1 = R_2 = R_3 = R$$

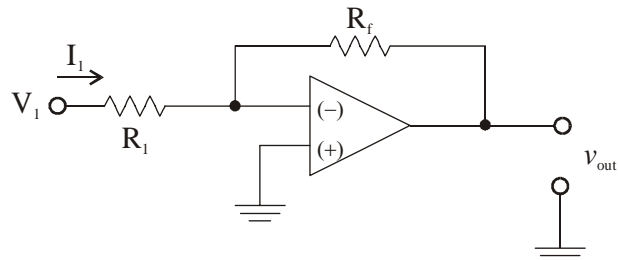
$$\Rightarrow v_{out} = -\frac{R_F}{R}(v_1 + v_2 + v_3)$$

⇒ = sum of voltages, with weights R_F/R_i

Example 5

Current-to-Voltage Converter

Inverting amplifier useful when we require an output voltage proportional to the current flowing into the input.



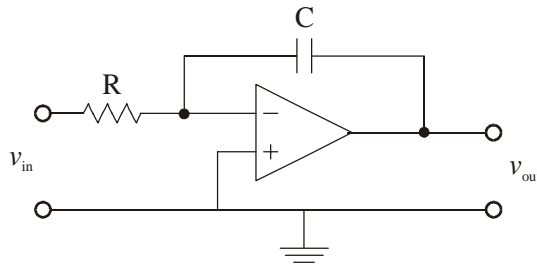
No current flows into (-) input ⇒

I_1 through R_1 goes through R_f

$$\left(I_1 = \frac{V_1}{R_1} \right)$$

$v_{out} = -I_1 R_f$ since other end at virtual ground

Example 6
Integrator



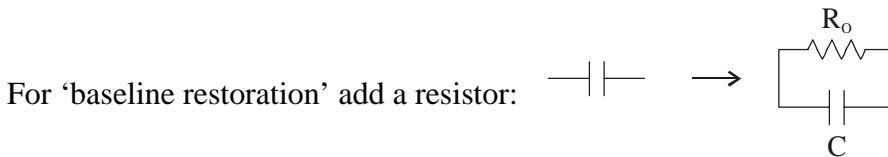
current through resistor $\left(\frac{v_{in}}{R}\right)$ + current through cap = 0

$$\Rightarrow C \frac{dv_{out}}{dt} + \frac{v_{in}}{R} = 0 \quad \left(I = C \frac{dv}{dt} \right)$$

$$v_{in} = v_{in}(t), \text{ integrate w.r.t. time } \Rightarrow \int_0^t \frac{dv_{out}}{dt} dt = -\frac{1}{RC} \int_0^t v_{in}(t) dt$$

$$v_{out}(t) = -\frac{1}{RC} \int_0^t v_{in}(t) dt + v_{out}(0)$$

VERY IMPORTANT PHYSICS CIRCUIT – Integrate charge from a detector element.
Use switches to set initial conditions ($v_{out}(0) = 0$)



If $R_o C \gg t$, the integration time, this has little effect, but discharges the capacitor for long times.

Concepts

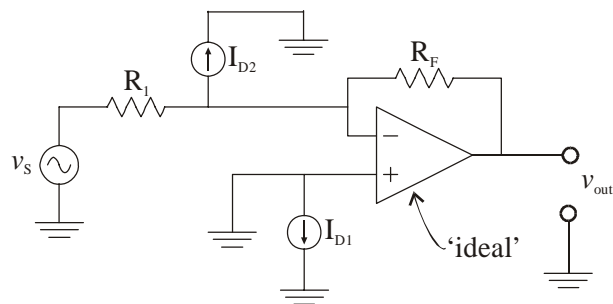
Op-Amp Circuit Design Considerations

- 1) voltage offset
 $V_+ = V_-$ by shorting inputs, output $\neq 0$
- 2) offset currents
input bias current = DC current flowing through two input terminals

Difference in two bias currents can lead to a voltage offset. e.g.:

I_{D1} has no effect, it’s current just goes to ground.

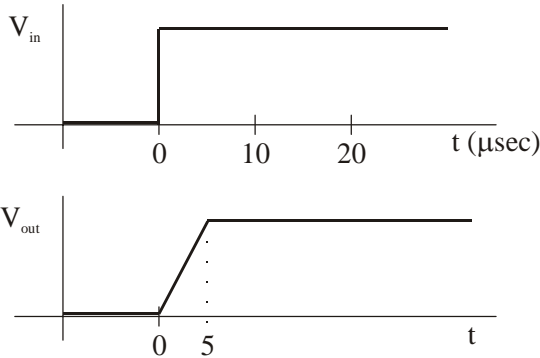
Short v_s to ground, ask what is the DC output



- ⇒ No voltage across R_1 [(+) is grounded ⇒ (-) = ground ⇒ both ends of R_1 are grounded]
- ⇒ Current I_{D2} flows through R_F ⇒ $v_{out} = I_{D2} R_F$
 $I_{D2} = 1 \mu A, R_F = 1k \Rightarrow v_{out} = 1mV$
- ⇒ Small DC offset from input offset current (distinct from offset voltage)
- ⇒ This stuff normally trimmed internally by trim circuits.
 Temperature variation of nulling ⇒ DRIFT
 (that's why internal compensation works better)

Slew Rate

∃ limitations on the speed at which the output voltage of the op-amp can change.
 Input changes suddenly ⇒ output takes a finite time to reach the new value.
 This process is called slewing.
 max rate that output can move to new value = max slew rate
 e.g. for follower, you might have



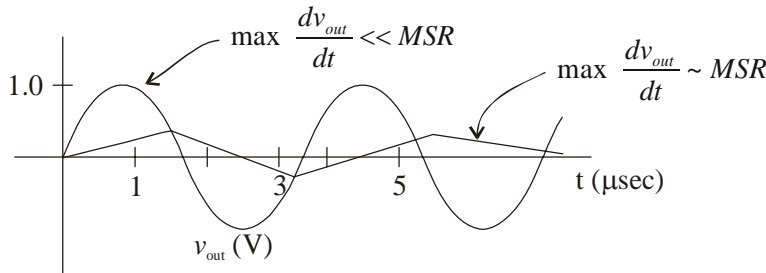
$$MSR = \frac{5V}{5 \mu sec} \sim 10^6 V/sec$$

Sinusoidal signal:

$$v_{in} = V_o \cos \omega t$$

$$v_{out} = A' v_{in} \Rightarrow \frac{dv_{out}}{dt} = A' \frac{dv_{in}}{dt} = -A' \omega V_o \sin \omega t \text{ volts/sec}$$

$$\max \frac{dv_{out}}{dt} = A' \omega V_o$$



Note that in the second case, op-amp slews all the time, first trying to catch up with the input in the uphill direction, then chasing it downhill.

Slope of lines = ± MSR ⇒ you can measure on scope.

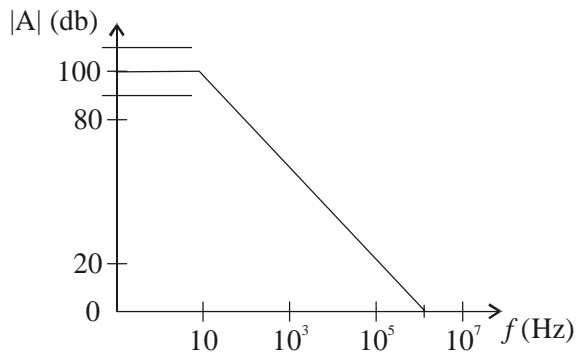
Characteristics

- 1) onset of slew-rate distortion depends on output amplitude and frequency

2) output amplitude is reduced & waveform is distorted

Frequency Response of Op-Amp Circuits

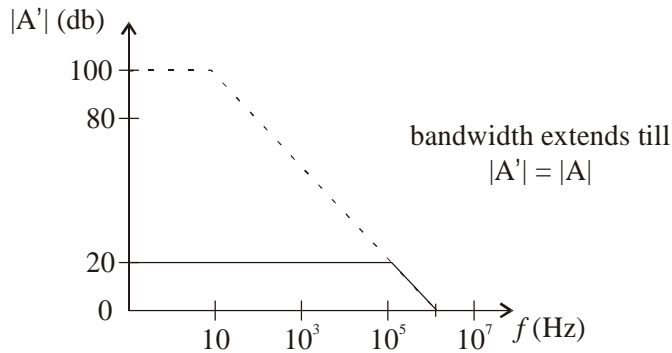
For a typical op-amp: (no feedback ‘open loop’)



Define bandwidth \equiv range of frequencies over which |A| is within 3db of max \Rightarrow open-loop bandwidth ~ 10 Hz.

Negative feedback makes gain insensitive to A..... for inverting amp, $A' = -R_F/R_1$

Choose $A' \sim 10$, then plot vs. $f \Rightarrow$



\Rightarrow A trade-off between gain & bandwidth, or gain-bandwidth product = constant. ‘Typical’ amp has gain-bandwidth product of $\sim 10^6$ Hz.

To get more gain@ fixed bandwidth \Rightarrow add more stages of amplification.

N.B. Frequency limitation above 10^5 Hz not same as slewing problem:

- onset depends on frequency, not amplitude
- no output waveform distortion for sinusoids