Physics 105
Aut 2012
Week 7

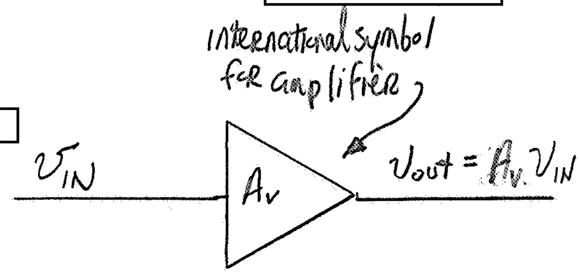
OP AMPS

IDEAL AMPLIFIERS + FEEDBACK

What is an ideal amp?

A_v = voltage gain

$$\text{Gain} \equiv \frac{v_{out}}{v_{in}} \longrightarrow A_v\ (\text{gain}) \to \infty$$
$$Z_{IN} \to \infty$$
$$Z_{OUT} \to 0$$

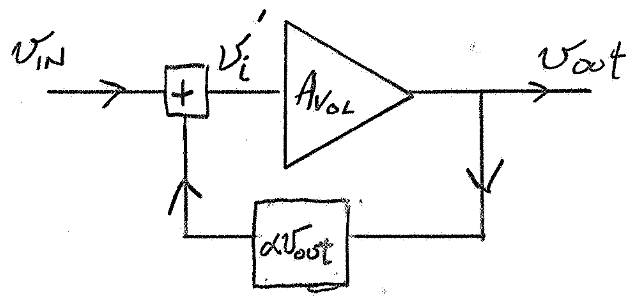


where $A_v \equiv \frac{v_{out}}{v_{in}}$ (voltage gain)

Problem: Gain not constant (cf - transistor β)

Solution: FEEDBACK!!

(block diagram, not schematic →)



A_{VOL} = "open loop" gain

α = fraction of output returned to input
$|\alpha| \leq 1$

By def'n of A_{VOL}, $v_{out} \equiv A_{VOL} v_i'$

$$= A_{VOL}(v_{IN} + \alpha v_{out})$$

Gain of entire circuit? $\boxed{A_F \equiv \left.\frac{v_{out}}{v_{IN}}\right|_{w/\text{feedback}} \underset{(\text{algebra})}{=} \frac{A_{VOL}}{1 - \alpha A_{VOL}}}$

A_F = "closed loop gain" (gain w/ Feedback)

CONSEQUENCES?

i) Negative Feedback, $\alpha < 0$

As $A_{VOL} \to \infty$, $A_F \to \frac{+1}{|\alpha|}$ → INDEPENDENT OF A_{VOL}!
and $A_F \geq 1$

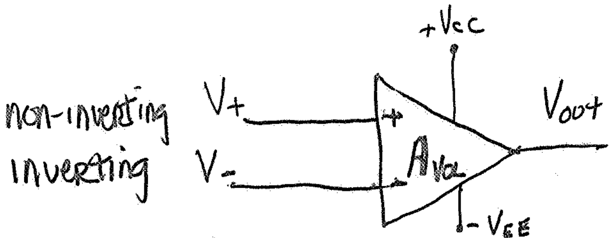
ii) Positive Feedback, $\alpha > 0$

As $(\alpha A_{VOL}) \to 1$, $A_F \to \infty$ → INSTABILITY
→ can result in oscillations

can be good or bad

Op-Amp - "Operational Amplifier"

- Differential Amp w/ ridiculous gain ($A \sim 10^5 - 10^6$) to take advantage of negative feedback.
- when used properly, extremely easy to use, extremely stable



GAIN = A_{VOL} ("voltage gain, open loop")

$$\boxed{V_{out} = A_{VOL}(V_+ - V_-)}$$

NOTE: OP AMPS / ALL IC's must have power supply

$+V_{cc}$, $-V_{EE}$

Ideal Op Amp Characteristics

	Reality
a) $Z_{IN} \to \infty$	$10^6 - 10^{14}\ \Omega$
b) $Z_{out} \to 0$	$< 10\ \Omega$
c) $A_{VOL} \to \infty$	$10^5 - 10^6$
d) Bandwidth $\to \infty$ (frequency range of operation)	1 - 5 MHz

"GOLDEN RULES" - apply when negative feedback is present

1) $V_+ \approx V_-$. Output does whatever it takes to make this true (via feedback)

2) $i_+ = i_- \approx 0$ inputs draw no current

Armed with these, very powerful but simple circuits can be devised.

PRACTICAL LIMITATIONS

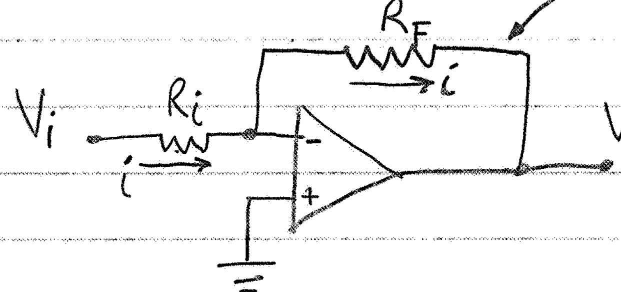
- Saturation at rails: $-V_{EE} < V_{out} < V_{cc}$
- Slew Rate : $\frac{d}{dt}(V_{out})$ is finite
- Finite input current: must have DC path to inputs/output
- Output Current Limited ~ 20-25 mA
- Frequency Response limited.

BASIC OpAmp CIRCUITS: -

[Combine OpAmp Rules with Kirchhoff, Thevenin]

A. INVERTING AMP

(negative feedback)



⟹ works for AC OR DC signals

Rule 1: Since $V_+ \approx V_- \implies V_- = 0$ "VIRTUAL GROUND"

Rule 2: i (thru R_i) = i (thru R_f)

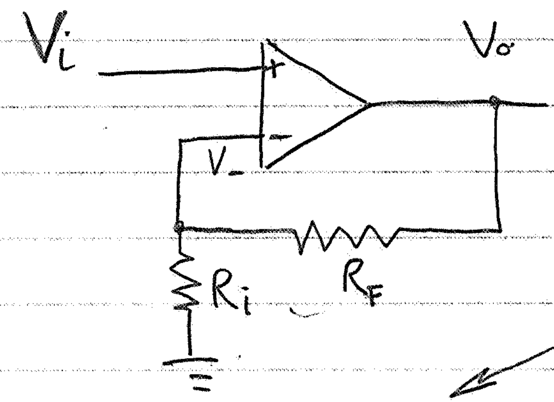
$$i = \frac{V_i - V_-}{R_i} = \frac{V_- - V_o}{R_F}$$

$$A_F = \boxed{\frac{V_o}{V_i} = \frac{-R_F}{R_i}}$$

Independent of A_{VOL}!! (Remember emitter follower, independent of β?)

Q - what is limit on gain?
A - saturation at the rails.
Why? There are transistors inside op amps!

B. Non-Inverting Amp



Note: signal input is to (+) input, but feedback still goes to (-) input. Compare with inverting amp.

Q. why can we use volt. divider?
A. no current flowing out of V_-

2 ways to solve → $V_- = V_o \dfrac{R_i}{R_i + R_F}$. → But $V_- = V_i$ (golden rule)

Since $i_{R_F} = i_{R_i}$

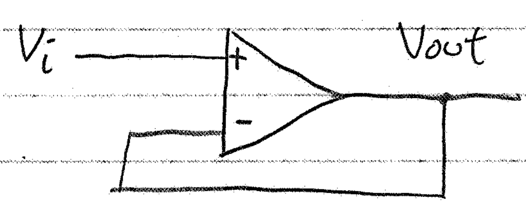
$$\frac{V_i - 0}{R_i} = \frac{V_o - V_i}{R_F} \quad \overset{\text{solve}}{\Longrightarrow} \quad \boxed{A_F = \frac{V_o}{V_i} = 1 + \frac{R_F}{R_i}}$$

C. Follower or Unity Gain Buffer

Let $R_F \to 0$, $R_i \to \infty$ above.

Then $A_F = 1$

$\Longrightarrow V_{out} = V_{IN}$



So What? $Z_{IN} \approx \infty$, $Z_{out} \approx 0$

This is a follower, or impedance "buffer", a chimpanzee can use.

That's what.

LECTURE 7A

- More opamp circuits
- Non-Ideal Op Amp Models

MORE CIRCUITS

A. Phototransistor: Current → Voltage converter - (TRANSIMPEDANCE AMP

transimpedance amp = transfer function has units in ohms. See result below.

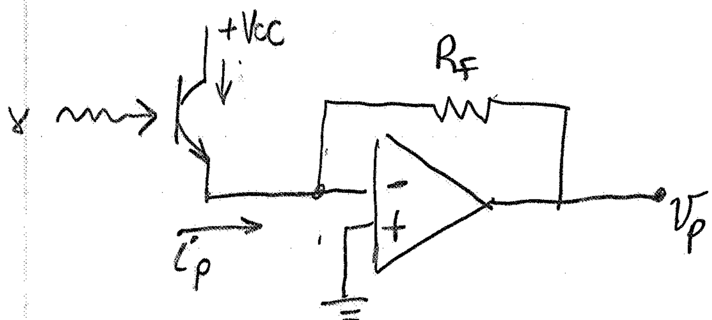
Photodetectors:

Photodiodes - FAST
Phototransistors - sensitive to very low light
Photomultipliers - " " even less light

cf neutrino detectors

(vacuum tubes, high voltage)

Photodetectors are always current sources - via photoelectric effect. In a phototransistor, photons create charge carriers which become base current to turn on the transistor. Typical application:



Note: as drawn,
$V_{CE} = +V_{cc} - 0$
$= +V_{cc}$

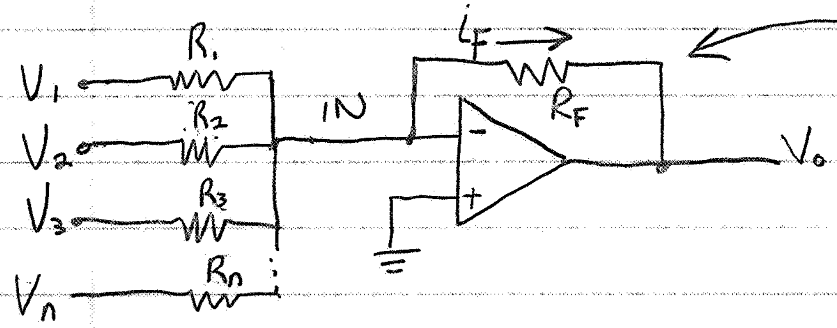
V_{CE} for transistor is fixed at $(+V_{cc} - 0) = +V_{cc}$, so that $i_p \sim$ Intensity of incoming light $\sim$ photons/sec.
↳ "photocurrent"; where

$$i_p = \frac{0 - v_p}{R_F} \Longrightarrow v_p = -i_p \cdot R_F$$

output voltage proportional to i_p. R_F is the "gain" resistor.

* Note the general rule, here and with photodiodes in Lab 2: provide a definite external bias ⟹ photocurrent proportional to light intensity

B. Summing Amp with Gain



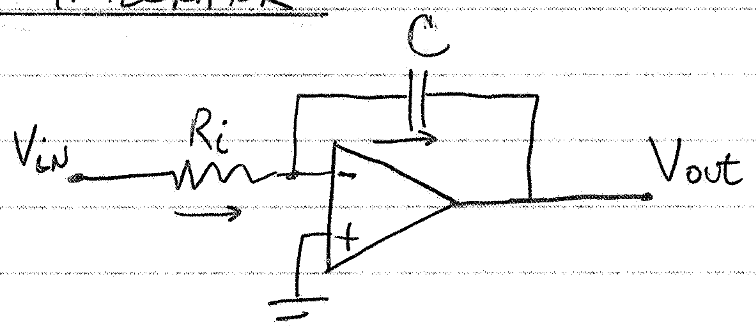
$i_F = \sum^n i_{R_n}$

$V_{out} = -i_F R_F$ $\quad$ ($V_- = 0$, remember?) $\;= V_+$

$= -R_F \sum^n i_{R_n} = -R_F \sum^n \left(\frac{V}{R}\right)_n$

If all R's are =, $R_1 = R_2 = R_n = R$, then $\boxed{V_{out} = -\frac{R_F}{R} \sum^n V_n}$

C. INTEGRATOR



$V_{out} = 0 - V_c$

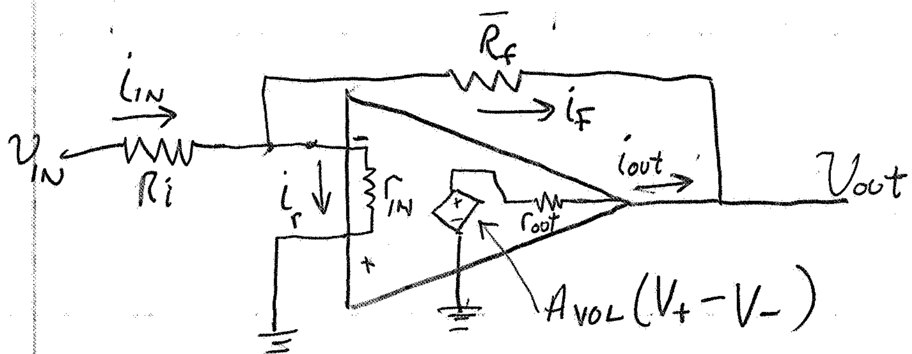
But $i_c = C\frac{dV_c}{dt} = -C\frac{dV_{out}}{dt} = \frac{V_{IN} - 0}{R}$

So $\boxed{V_{out} = -\frac{1}{RC}\int_0^t V_{IN}\, dt'}$

Compare to plain-vanilla RC circuit: Op amp does not require $V_{out} << V_{IN}$!!

Pitfall: small assymetries in input get integrated ⟹ DC offset. See p. 186 in Lab Manual

NON-IDEAL GAIN



$i_{OUT} = -i_F$

Ignore r_{out} (since factors of $i_{out} r_{out}$ are small).
Relax the $i_+ = i_- = 0$ assumption.
Then:

$$i_{IN} = i_F + i_r$$

(1) $$\frac{V_{IN} - V_-}{R_i} = \frac{V_- - V_{out}}{R_f} + \frac{V_- - V_+}{r_{IN}}$$

Use the fact that $V_+ = 0$, and $V_{out} \equiv A_{VOL}(V_+ - V_-)$

$$\Longrightarrow V_- = \frac{-V_{out}}{A_{VOL}}$$

Substitute for V_- and V_+ in (1) above, turn the algebra crank:

$$A_{v\,\text{closed loop}} \equiv \frac{V_{out}}{V_{IN}} = \frac{-R_f}{\frac{R_i + R_f}{A_{VOL}} + \frac{R_i R_f}{r_{IN} A_{VOL}} + R_i}$$

As $A_{VOL} \to \infty$, $A_v \to -R_f/R_i$ as before

BUT, what if $A_{VOL} < \infty$?

Let $R_i = 1K$, $R_f = 10K$, $r_{IN} = 10^6 \Omega$:

Then

A_{VOL} (dB)	A_v (dB)
10^5 (100)	9.999 (20)
10^2 (40)	9.009 (19)
10^1 (20)	4.762 (13.5)
10^0 (0	0.833 (-1.6)

Closed loop gain drops as A_{VOL} drops!

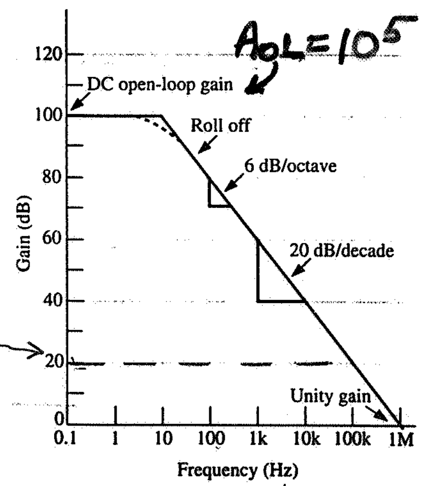
Why would A_{VOL} drop? $\longrightarrow$

What is reality? $A_{VOL} \to \infty$ and Δf (bandwidth) $\to \infty$ are not true.

A_{VOL} is designed to rolloff at high frequencies <u>for stability</u>

Typical gain Rolloff:

(closed loop) $A_V = 10$



741 op amp

SPECS:

- "GAIN BANDWIDTH PRODUCT"
  $A_{VOL}(f) \times \Delta f$ = const for a given opamp

- "UNITY GAIN BANDWIDTH": Δf when $A_F = 1$
  ~ 4 MHz (LF411)
  ~ 1 MHz (LM741)

IMPORTANT CONCLUSIONS:

1) Maintain A_F (CLOSED LOOP) $\ll$ A_{OL} (OPEN LOOP) at the frequencies of interest

2) Op Amp also behaves like RC low pass