BENG 186B: Principles of Bioinstrumentation Design

Lecture 5

Amplifiers and Active Linear Circuits for Signal Processing

References

Webster, Ch. 3 (Sec. 3.1-3.4, 3.11, 3.12).

http://en.wikipedia.org/wiki/Rectifier

http://en.wikipedia.org/wiki/Opamp

http://en.wikipedia.org/wiki/Active_filter

AMPLIFIERS AND SIGNAL PROCESSING

Webster, Chap. 3

- Passive circuits, made of R, L and C, cannot amplify signals: they can filter, but they do not provide gain (larger than one) because they do not provide power.

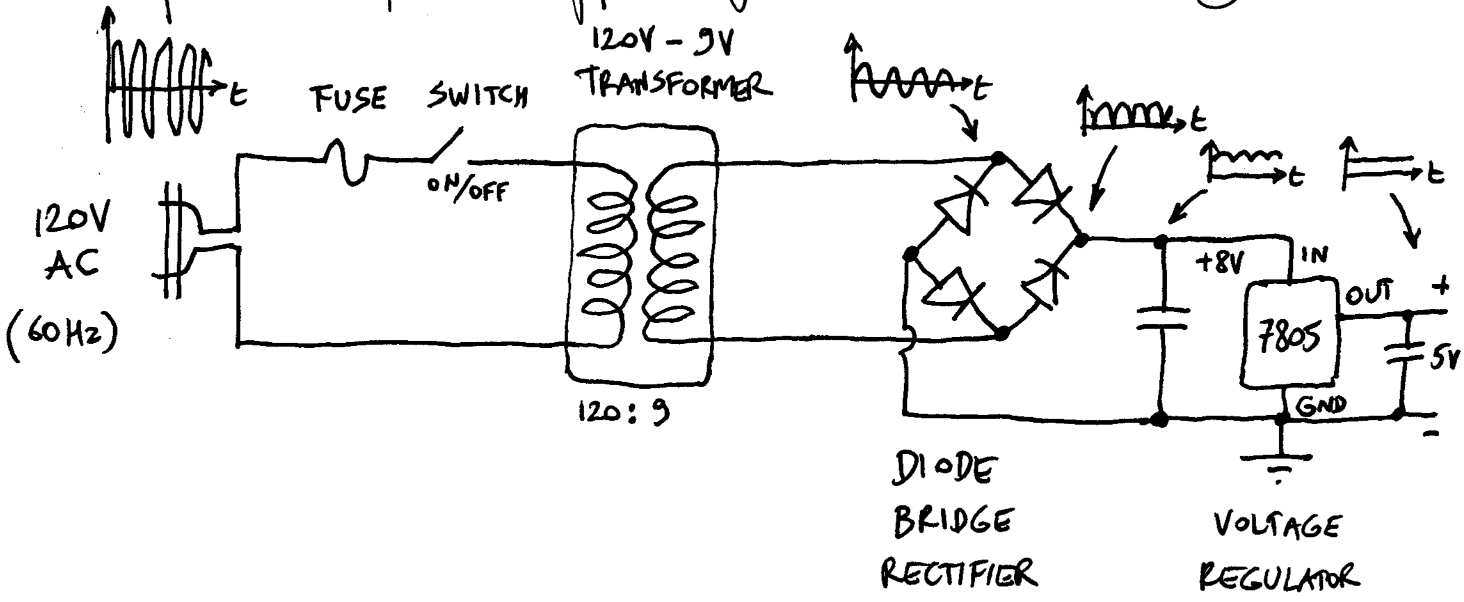
- Active circuits, such as amplifiers, are powered and can provide large amplification. Digital active circuits can further provide logic operations for digital signal processing. They require power supplies to function.

	PASSIVE CIRCUITS	ACTIVE CIRCUITS
COMPONENTS :	R, L, C M (mutual inductance)	Power supplies Op-amps Comparators Timers Digital gates etc...
USE :	Passive filtering	Amplification Buffering Active filtering Signal processing Decision making etc...

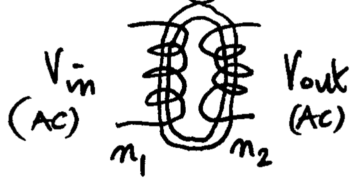
— Power supplies

- Most electronic devices, and all active devices, have a power supply
- Batteries are the easiest, but have limitations

Simple DC power supply from AC wall voltage:

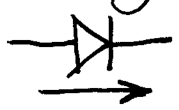


- Transformer : transforms AC voltages through mutual inductance



$$\frac{V_{out}(j\omega)}{V_{in}(j\omega)} = \frac{n_2}{n_1} \quad (\text{for } \omega > 0)$$

- Diode bridge : rectifies AC voltage to DC voltage



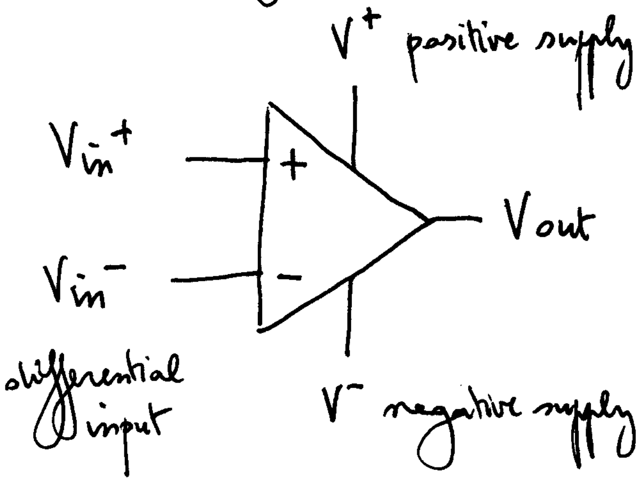
Diodes only conduct in one direction
⇒ only the positive part of the voltage waveform comes through

- Regulator: stabilizes DC voltage from IN to OUT as long as IN > OUT.

LM 7805 : OUT = +5V
LM 7812 : OUT = +12V

— Operational amplifiers (OP-AMPs)

→ differential amplifier with high DC gain



Typical op-amps :

$V^+ = +12V$ max

$V^- = -12V$ max

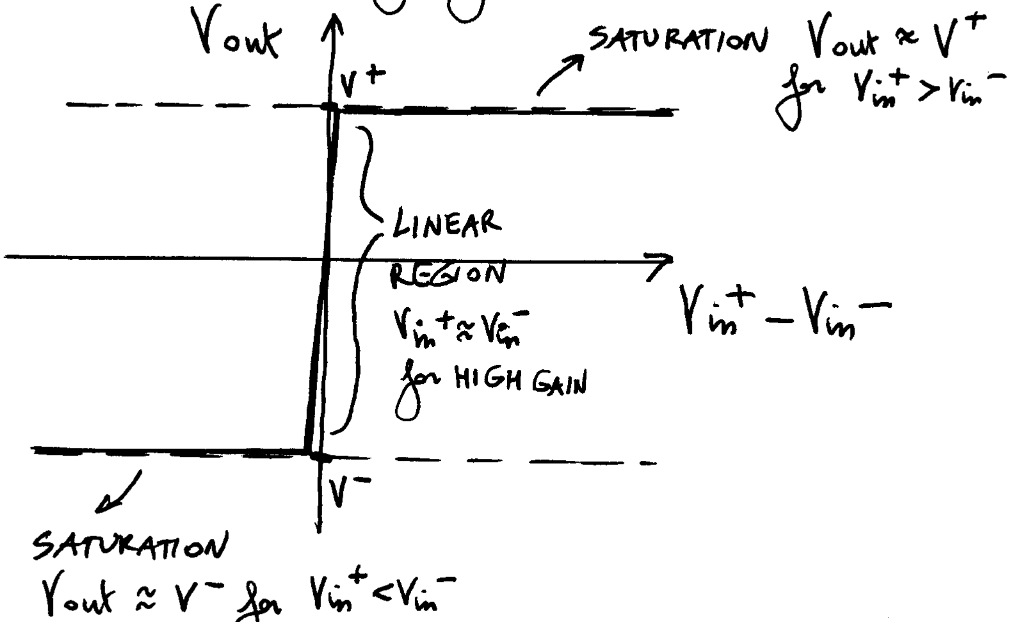
Modern (low voltage) op-amps:

$V^+ = 5V$, or $3V$

$V^- = 0V$ (GND)

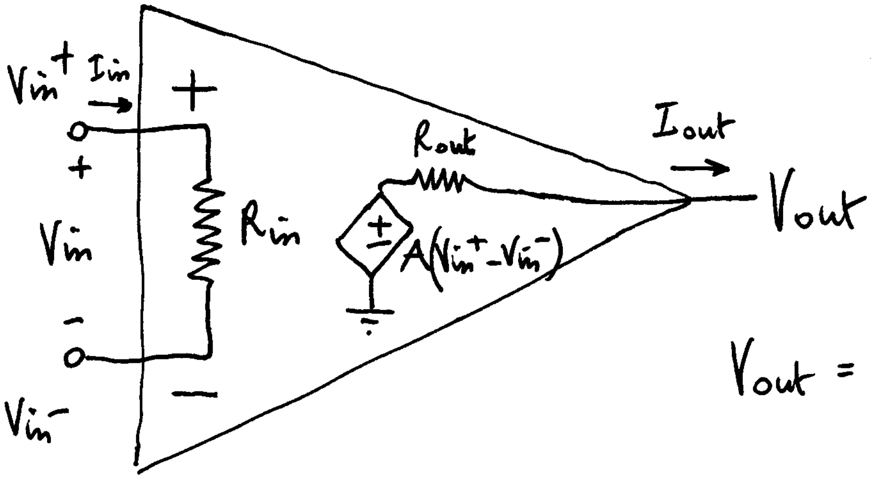
- The voltage supplies V^- and V^+ are important !

  The output V_{out} cannot go higher than V^+ or lower than V^-, no matter the voltage gain



Op-amps are designed to operate in the LINEAR REGION, where the output is not saturated, and for which the two inputs are approximately equal $V_{in}^+ \approx V_{in}^-$ in the limit of HIGH GAIN.

- Linear model of the op-amp:



$$V_{out} = A(V_{in}^+ - V_{in}^-) - R_{out} \cdot I_{out}$$

$$V_{in} = V_{in}^+ - V_{in}^- = R_{in} \cdot I_{in}$$

$$\left\{\begin{array}{l} A: \text{VOLTAGE GAIN (differential)} \\ R_{in}: \text{INPUT IMPEDANCE (resistance)} \\ R_{out}: \text{OUTPUT IMPEDANCE (resistance)} \end{array}\right.$$

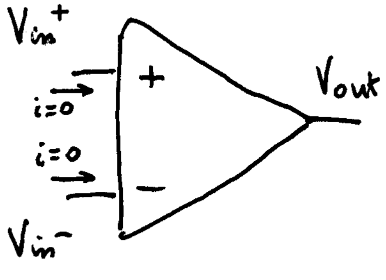
- Typical op-amp: e.g: "OP27"

$$\left\{\begin{array}{l} A \sim 10{,}000 \text{ (large)} \\ R_{in} \sim 1\,T\Omega = 10^{12}\,\Omega \text{ (large)} \\ R_{out} \sim 50\,\Omega \text{ (relatively small - depends on power consumption)} \end{array}\right.$$

- "Ideal" op-amp:

$$\left\{\begin{array}{l} A \rightarrow \infty \\ R_{in} \rightarrow \infty \\ R_{out} \rightarrow 0 \end{array}\right.$$

$\Rightarrow$



:

- no current into V_{in}^+ node
- no current into V_{in}^- node
- $V_{in}^+ \approx V_{in}^-$

Analysis of linear active circuits with IDEAL opamps:

PRINCIPLE : Nodal analysis (don't even attempt mesh analysis)

→ Label all unknown node voltages

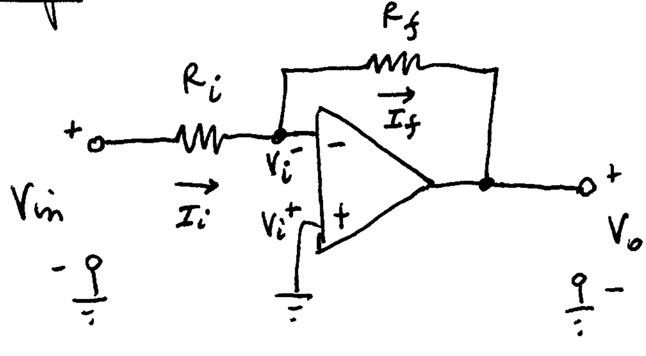
→ Apply KCL on all nodes except op-amp OUTPUTS (as well as VOLTAGE SOURCES)

→ For each op-amp, add an equation that $V_{in+} = V_{in-}$

⇒ Should have same number of equations as unknowns

→ Solve the linear set of equations for the node voltages

<u>Example</u>: INVERTING AMPLIFIER



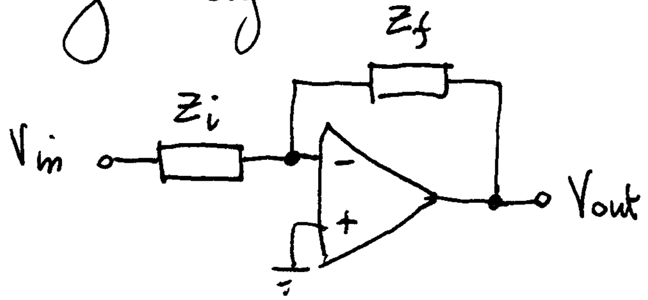
→ $V_i^- = V_i^+ = 0$

→ KCL @ V_i^- : no current IN the op-amp ($I_i = I_f$)

$$\Rightarrow \quad \frac{V_{in}}{R_i} = -\frac{V_{out}}{R_f}, \quad \text{or} \quad V_{out} = \underbrace{-\frac{R_f}{R_i}}_{\text{NEGATIVE GAIN}} \cdot V_{in}$$

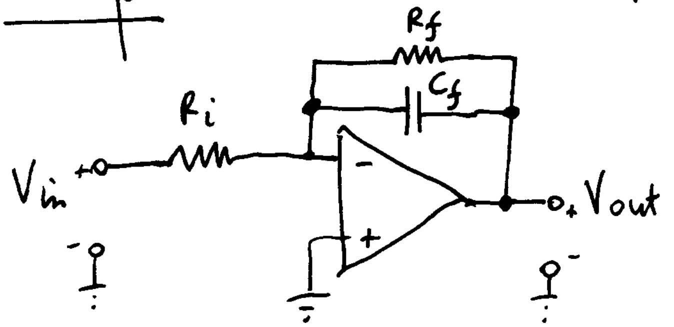
(inverting)

More generally:



$$\frac{V_{out}(j\omega)}{V_{in}(j\omega)} = -\frac{Z_f(j\omega)}{Z_i(j\omega)}$$

Example : ACTIVE FIRST-ORDER LOWPASS FILTER



: Inverting amplifier with

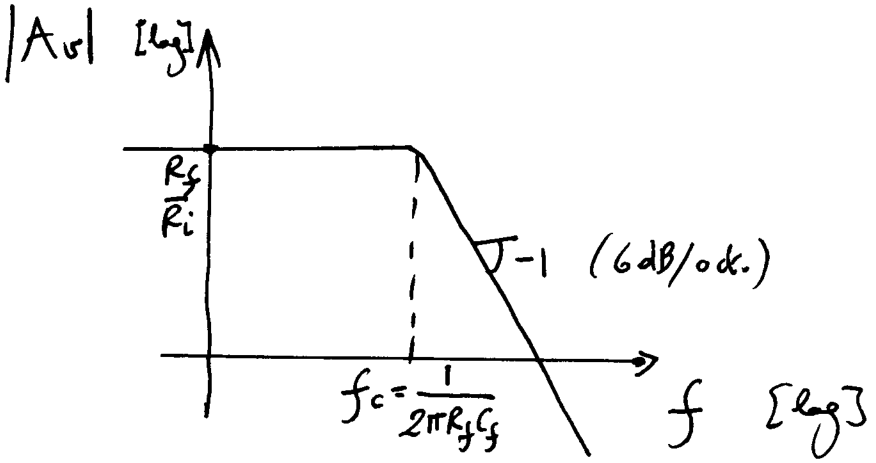
$$Z_i = R_i$$

$$Z_f = R_f \mathbin{//} \frac{1}{j\omega C_f}$$

$\downarrow$ PARALLEL combination

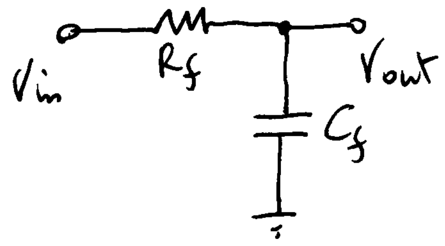
$$\Rightarrow \frac{V_{out}(j\omega)}{V_{in}(j\omega)} = -\frac{Z_f}{Z_i} = -\frac{\dfrac{R_f\cdot\frac{1}{j\omega C_f}}{R_f+\frac{1}{j\omega C_f}}}{R_i} = -\frac{R_f}{R_i}\cdot\frac{1}{1+j\omega R_f C_f}$$

$$\Rightarrow \text{voltage gain } A_v(j\omega) = A_{v0}\cdot\frac{1}{1+\frac{j\omega}{\omega_c}} \quad \text{with} \left\{\begin{array}{l} A_{v0} = -\frac{R_f}{R_i} \\ \text{DC GAIN} \\ \omega_c = 2\pi f_c = \frac{1}{R_f C_f} \\ \text{CUT-OFF} \end{array}\right.$$



In contrast to the PASSIVE R-C FILTER, the active filter has a gain that can be greater than unity (in absolute value)

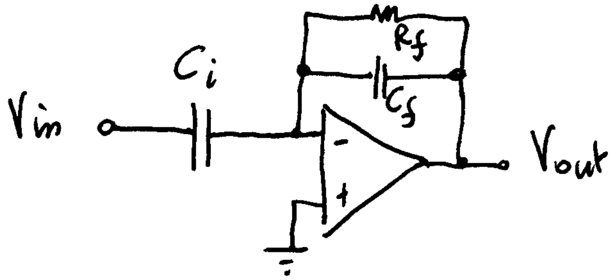
PASSIVE R-C :



$$A_{v0} = 1$$

$$\omega_c = 2\pi f_c = \frac{1}{R_f C_f} \text{ (SAME)}$$

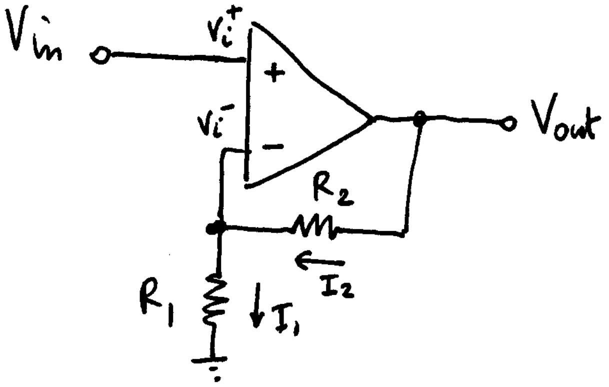
Variations: ACTIVE FIRST-ORDER HIGHPASS FILTER



$$\frac{V_{out}(j\omega)}{V_{in}(j\omega)} = -\frac{j\omega R_f C_i}{1 + j\omega R_f C_f}$$

etc...

Example: NON-INVERTING AMPLIFIER



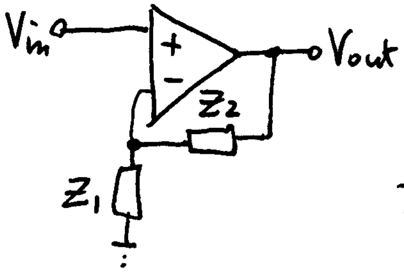
→ $V_i^+ = V_i^- = V_{in}$

→ KCL @ V_i^-: no current in the opamp

$I_1 = I_2$

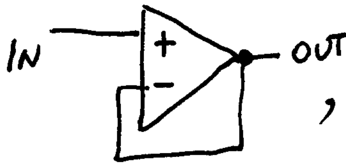
$$\Rightarrow \quad \frac{V_{in}}{R_1} = \frac{V_{out} - V_{in}}{R_2}, \quad \text{or} \quad V_{out} = \underbrace{\left(1 + \frac{R_2}{R_1}\right)}_{\text{POSITIVE (non-inverting) GAIN, } A_v \geq 1} \cdot V_{in}$$

- More generally:

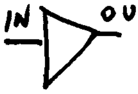


$$\frac{V_{out}(j\omega)}{V_{in}(j\omega)} = 1 + \frac{Z_2(j\omega)}{Z_1(j\omega)}$$

- Special case: BUFFER : $Z_1 = \infty$
(UNITY GAIN AMP.) $Z_2 = 0$



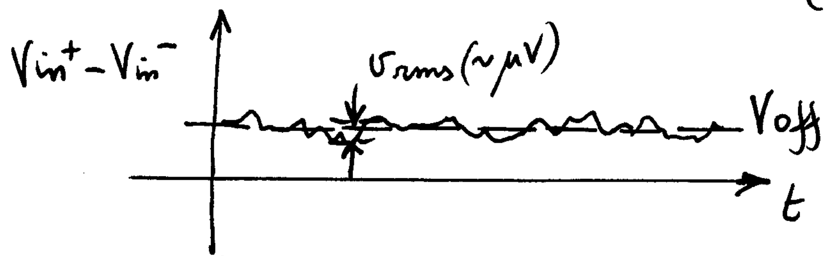
, or



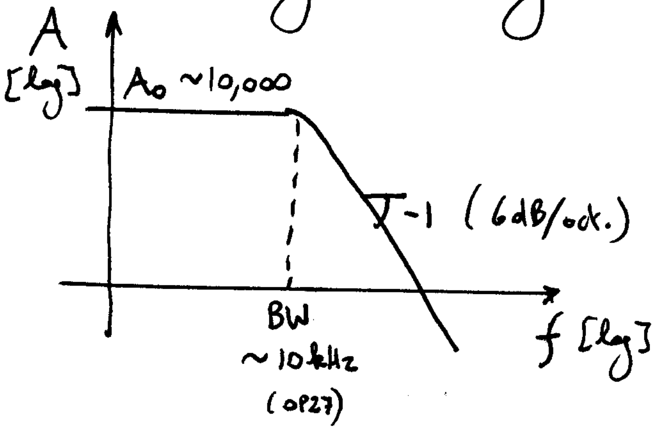
$\Rightarrow$ OUT = IN , but : $Z_{in} = \infty$: good to boost weak signals
$Z_{out} = 0$

current flowing in at zero input voltage

- Non-ideal characteristics of OP-AMPS :
  - finite A ~10,000 , finite R_{in} ~TΩ , non-zero R_{out} ~50Ω , non-zero bias current ~pA
  - Input offset voltage : $V_{in}^{+} - V_{in}^{-} = V_{off}$, typically mV
    may drift with temperature
  - Input referred voltage noise $V_{in}^{+} - V_{in}^{-} = v_{rms}$
    $\downarrow$ root-mean-square AC noise voltage (typically μV)



  - Finite bandwidth : gain is a function of frequency :



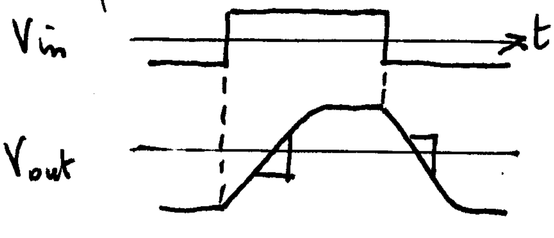
A_0 : DC gain

BW : bandwidth (f_c) for maximum gain (A_0)

Gain-bandwidth product : $A_0 \cdot BW = A(f) \cdot f$ at high frequency

e.g. :
$A(10kHz) = 10{,}000$
$A(1MHz) = 100$
$A(100MHz) = 1$

  - Finite slew rate : slope dV_{out}/dt is limited, both upgoing & downgoing :



typically ~ 100V/μs