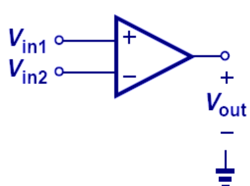
Lecture 3: Opamp Review

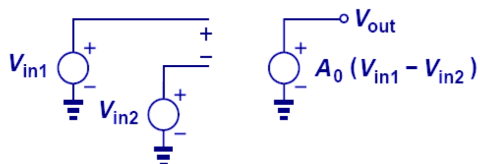
- Inverting amplifier
- Generalized impedances
  - Inverting integrator
  - Inverting differentiator
- Weighted summer
- Non-inverting amplifier
- Voltage buffer
- Non-linear amplifiers

First, assume ideal op amp.

Basic Opamp

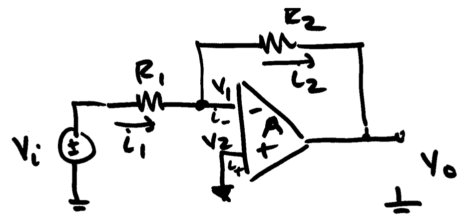
- Op amp is a circuit that has two inputs and one output.
- It amplifies the difference between the two inputs.





Inverting Amplifier

- Note:
  - Negative feedback
  - Find close loop gain
- Analysis



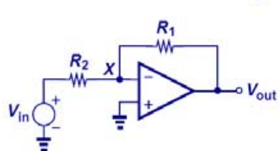
<u>Virtual short circuit:</u> Due to infinite gain of op amp, the circuit forces V_2 to be close to V_1, thus creating a virtual short.

Closed loop gain

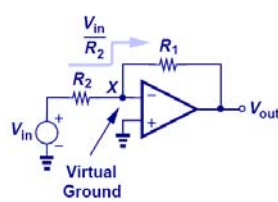
$$\frac{V_0}{V_i} = -\frac{R_2}{R_1}$$

Inverting Amplifier

- Note that the virtual ground is not actually shorted to ground; otherwise this would force all the current flowing through R2 to ground and Vout would be zero.



(a)



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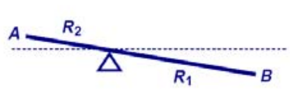
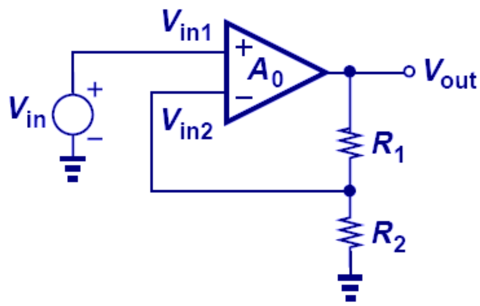


(c)

- The behavior of the virtual ground is similar to a seesaw, where the point between the two arms is pinned (does not move), allowing the displacement at point A to be “amplified” (and “inverted”) at point B.

Non-inverting amplifier

- A noninverting amplifier returns a fraction of output signal thru a resistor divider to the negative input.
- With a high Ao, Vout/Vin depends only on ratio of resistors, which is very precise.

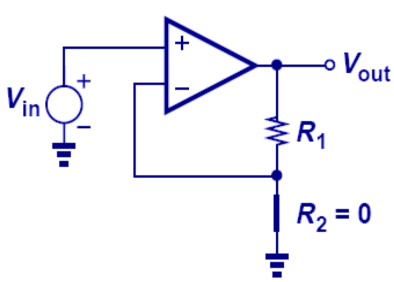


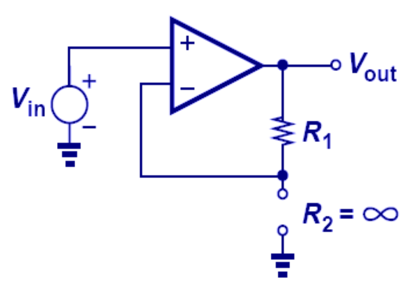
Closed loop gain

$$\frac{V_{out}}{V_{in}} = \frac{R_2 + R_1}{R_2} = 1 + \frac{R_1}{R_2}$$

Extreme Cases of R_2 (Infinite A_0)

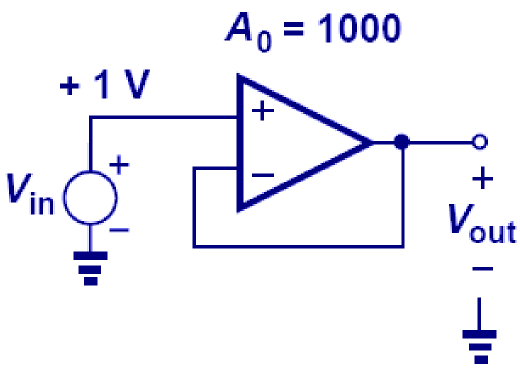
- If R2 is zero, the loop is open and Vout /Vin is equal to the intrinsic gain of the op amp.
- If R2 is infinite, the circuit becomes a unity-gain amplifier and Vout /Vin becomes equal to one.





Unity Gain Amplifier

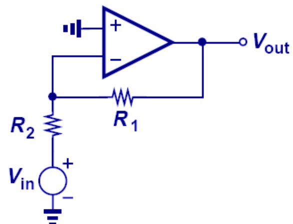
- Why use this if Vout=Vin?



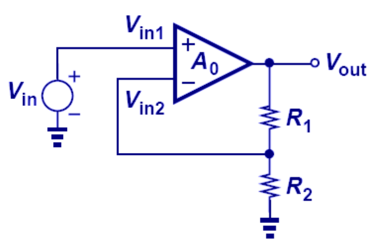
Another View of Inverting Amplifier

- For large R1/R2, magnitude of closed loop gain is roughly the same. Why use one over the other?

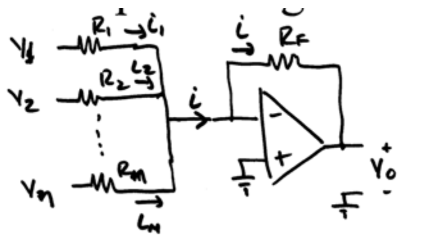
Inverting



Noninverting



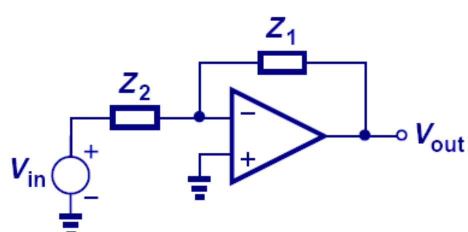
Voltage Adder or Weighted Summer



Ref. Sedra and Smith, Fig. 2.10.

- Input currents:
- Current summation at inverting node:
- Output voltage:

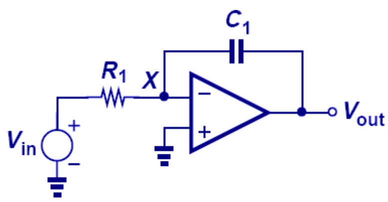
Complex Impedances Around the Op Amp

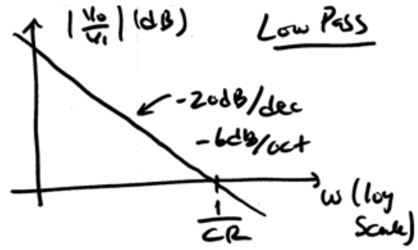


$$\frac{V_{out}}{V_{in}} \approx -\frac{Z_1}{Z_2}$$

- Replace R_1 and R_2 with impedances, Z_1 and Z_2.
- The closed-loop gain is still equal to the ratio of two impedances.
- Transfer function:
  - Magnitude
  - Phase

Example: Inverting Integrator





Time Domain

$$i_R(t) = \frac{V_{in}(t)}{R_1} \qquad q_C(t) = \int i_R(t)dt$$

$$v_{c1}(t) = \frac{q_C(t)}{C_1} = \frac{1}{C_1}\int i_R(t)dt$$

$$V_o(t) = -v_{c1}(t) = -\frac{1}{C_1}\int i_R(t)dt = \frac{1}{R_1C_1}\int V_{in}(t)dt$$

$$V_{out} = -\frac{1}{R_1C_1}\int V_{in}dt$$

Frequency Domain

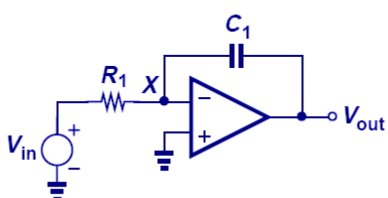
$$\frac{V_{out}}{V_{in}} = -\frac{1}{R_1C_1s} \qquad \frac{V_{out}(s)}{V_{in}(s)} = -\frac{1}{R_1C_1s}$$

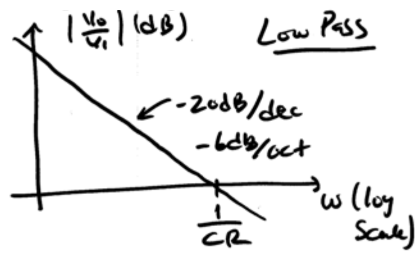
$$\frac{V_{out}(j\omega)}{V_{in}(j\omega)} = -\frac{1}{j\omega R_1C_1} \qquad \left|\frac{V_{out}(j\omega)}{V_{in}(j\omega)}\right| = \frac{1}{\omega R_1C_1} = \frac{\omega_{\text{int}}}{\omega}$$

$$\angle\frac{V_{out}(j\omega)}{V_{in}(j\omega)} = 90 \qquad \omega_{\text{int}} = \frac{1}{R_1C_1}$$

$$\frac{V_{out}}{V_{in}} = -\frac{1}{R_1C_1s}$$

Example: Inverting Integrator





$\omega_{\text{int}} = \frac{1}{R_1C_1}$ Is the integrator frequency

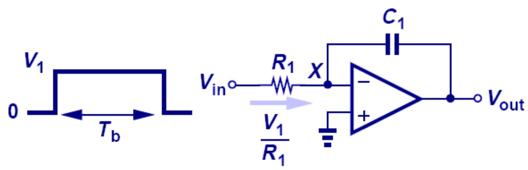
Frequency Domain

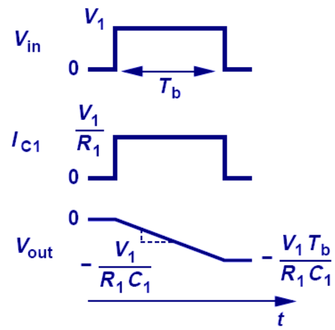
Note that at ω=0, the impedance of C1 is infinite and the opamp operates open loop (i.e. no negative feedback). That is, the gain at DC is infinite, as the open loop gain is infinite. This should also be obvious from the transfer function:

$$\frac{V_{out}}{V_{in}} = -\frac{1}{R_1C_1s}$$

where the root of the denominator, or pole of the transfer function, is at zero (i.e. DC). In practice, since at DC the opamp is in open loop configuration, any DC offsets will saturate the output. How do you fix this?

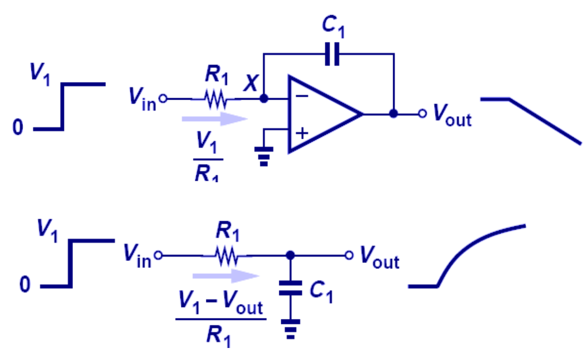
Integrator with Pulse Input



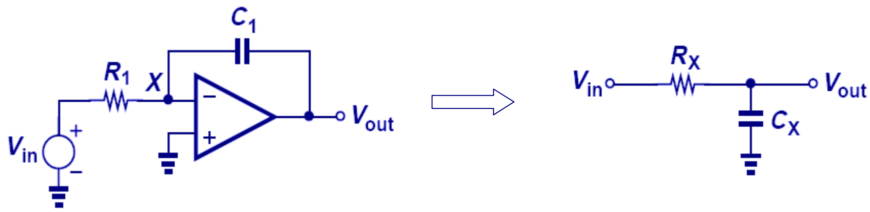


$$V_{out} = -\frac{1}{R_1 C_1}\int V_{in} dt = -\frac{V_1}{R_1 C_1} t \quad 0 < t < T_b$$

Comparison of Integrator and RC Lowpass Filter



Lossy Integrator



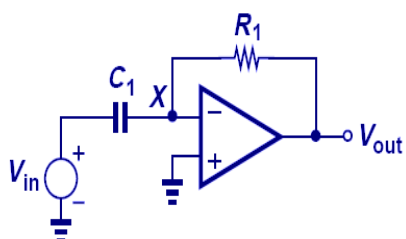
Consider the case when Ao is finite

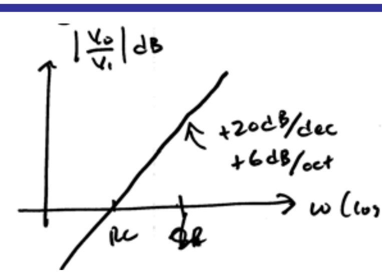
$$\frac{V_{out}}{V_{in}} = \frac{-1}{\frac{1}{A_0} + \left(1 + \frac{1}{A_0}\right) R_1 C_1 s}$$

- When finite op amp gain is considered, the integrator becomes lossy as the pole moves from the origin to -1/[(1+A_0)R1C1].
- It can be approximated as an RC circuit with C boosted by a factor of A_0+1

Note: pole frequencies are obtained by setting he denominator of the transfer function to zero

Differentiator





Time domain:

$i_1(t) = C \frac{dV_i(t)}{dt}$

$v_O(t) = -RC \frac{dV_i(t)}{dt}$

$$V_{out} = -R_1 C_1 \frac{dV_{in}}{dt}$$

$$\frac{V_{out}}{V_{in}} = -\frac{R_1}{\frac{1}{C_1 s}} = -R_1 C_1 s$$

Frequency domain:

$V_o(s)/V_i(s) = -\frac{R}{1/sC} = -sRC$

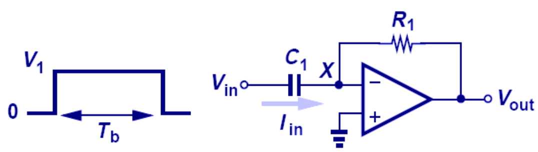
$|V_o(j\omega)/V_i(j\omega)| = \omega RC = \frac{\omega}{\omega_{DIFF}}$

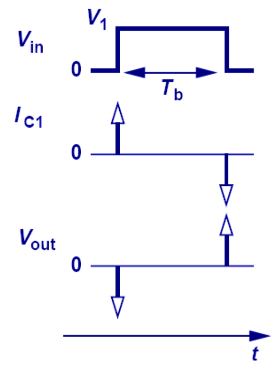
$\angle V_o(j\omega)/V_i(j\omega) = -90$ ↓

$\frac{V_o(j\omega)}{V_i(j\omega)} = -j\omega RC$

$\omega_{DIFF} = \frac{1}{RC}$

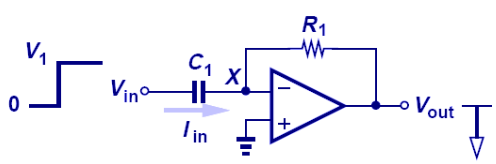
Differentiator with Pulse Input

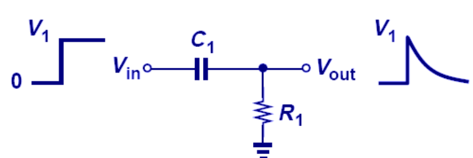




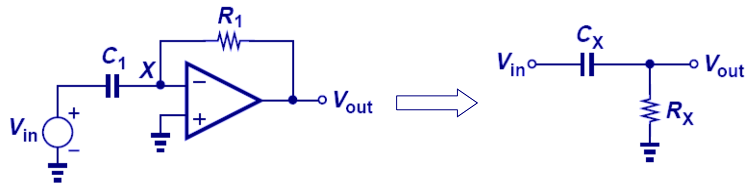
$$V_{out} = \mp R_1 C_1 V_1 \delta(t)$$

Comparison of Differentiator and High-Pass Filter





Lossy Differentiator



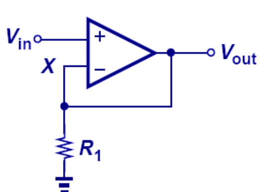
Consider the case when Ao is finite

$$\frac{V_{out}}{V_{in}} = \frac{-R_1 C_1 s}{1 + \frac{1}{A_0} + \frac{R_1 C_1 s}{A_0}}$$

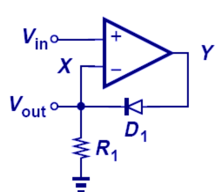
- When finite op amp gain is considered, the differentiator becomes lossy as the zero moves from the origin to $-(A_0+1)/R1C1$.
- It can be approximated as an RC circuit with R reduced by a factor of (A_0+1).

Precision Rectifier

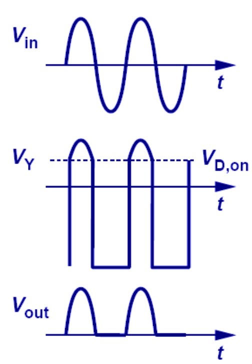
Suppose we want to eliminate the diode voltage drop (i.e. dead zone) associated with a simple rectifier circuit.



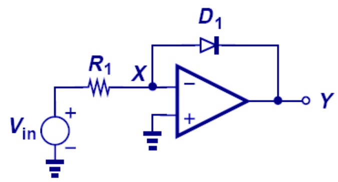
Assume a unity-gain buffer tied to the resistive load. High gain of opamp ensures X tracks Vin.

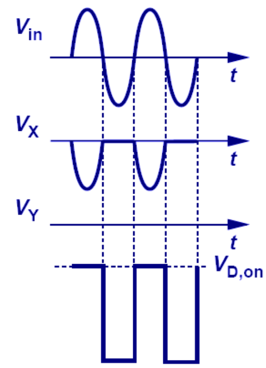


Insert a diode to "break" connection and hold X at zero during negative cycles. Assume Vin=0; the opamp raises Vy to Vdon1 to hold X at roughly zero. If Vin becomes positive, X tracks. If Vin becomes negative, Vy goes negative. Since D1 cannot carry current (reversed biased), the opamp produces a very large negative output (near the negative rail).



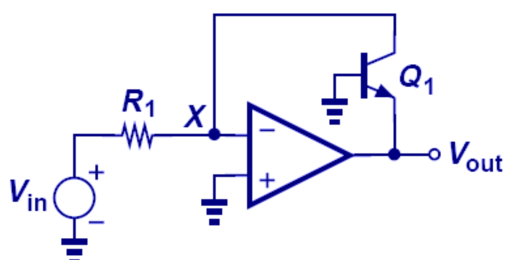
Inverting Precision Rectifier





- When V_{in} is positive, the diode is on, V_y is pinned around $V_{D,on}$, and V_x at virtual ground.
- When V_{in} is negative, the diode is off, V_y goes extremely negative, and V_x becomes equal to V_{in}.

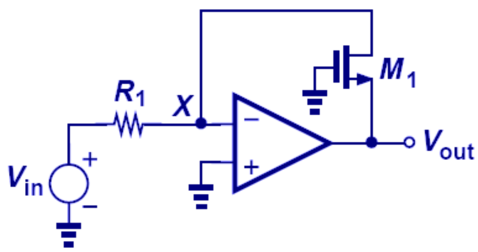
Logarithmic Amplifier



$$V_{out} = -V_T \ln \frac{V_{in}}{R_1 I_S}$$

- By inserting a bipolar transistor in the loop, an amplifier with logarithmic characteristic can be constructed.
- This is because the current to voltage conversion of a bipolar transistor is a natural logarithm.
- Logamps are useful in applications where the input signal may vary by a large factor. In such cases, weak signals are amplified and strong signals are attenuated (compressed), hence the log dependence.
- Logamps implement the inverse function of the exponential characteristic

Square-Root Amplifier



$$V_{out} = -\sqrt{\frac{2V_{in}}{\mu_n C_{ox}\frac{W}{L}R_1}} - V_{TH}$$

- By replacing the bipolar transistor with a MOSFET, an amplifier with a square-root characteristic can be built.
- This is because the current to voltage conversion of a MOSFET is square-root.
- Similar to the logamp using a bipolar transistor in the feedback path, the square root amp implements the inverse function of the MOS quadratic current dependence on VGS