Operational Amplifier

- The Operational Amplifier (also: op amp, opamp, OPAMP) is a versatile building block of analog design.
- Op amps have been around since the 1940's and are still very widely used today.
- The OPAMP has a differential-input and a singled-ended output (outputs can be differential too).
- The OPAMP amplifies the voltage difference between the inverting and non-inverting inputs.

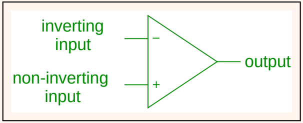


Figure: OPAMP schematic symbol

- The schematic symbol may or may not have V_{cc} and V_{ee} pins shown depending upon the application.

Operational Amplifier

- The output voltage (unloaded) is the difference between the inputs multiplied by the OPAMP gain. $V_o = AV_d = A(v_1 - v_2)$. This however is in the open loop (no feedback) situation.
- The gain A_d of the OPAMP is typically in excess of 10^6! This value A_d is called the open-loop gain. The OPAMP is almost never used without negative feedback due to the extremely high gain.
- The OPAMP's input resistance R_i is typically $\geq 2 * 10^9$ ohms, and its output impedance R_o is typically ≤ 25 ohms!
- Modern op amps very closely approximate an ideal differential amplifier.

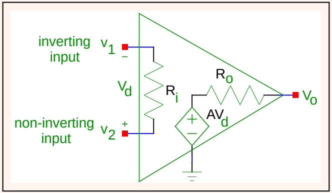


Figure: Non-ideal OPAMP model (Boyle Model)

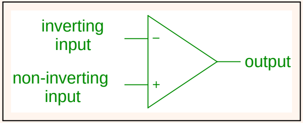
Operational Amplifier

- The "perfect" description on op amps can be applied to several parameters, but not all at once. You can optimize noise, distortion, input outset voltage, bandwidth, PSRR, CMRR, but not all at once.
- A brief sampling of near perfect op amp parameters:

Part	Parameter	Cost
LMH6629	-3dB small signal BW = 1GHz	5.00$
OPA140	$R_{in} = 10^{12}$ (tera) ohms	3.00$
OPA209	PSRR=0.055uV/V, G=$4 * 10^6$	2.00$
LT1115	THD= 0.002% into 600 ohm load	6.50$

Operational Amplifier

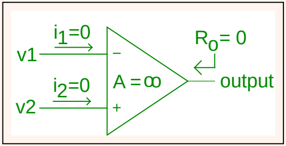
- Inputs applied to the "-" *inverting* terminal appear with the opposite polarity at the output.
- Inputs applied to the "+" *non-inverting* terminal appear with the same polarity at the output.



- How far the output and inputs can transition is limited by the power supply *rails*.
- A 100uV change at the inputs with a gain of 10^6 would send the output to the supply rails, not 100V!

Operational Amplifier

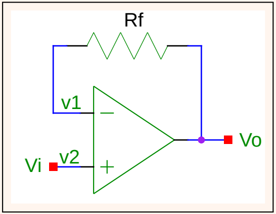
- We will consider the op amp to be ideal:
  - Infinite input impedance
  - Zero output resistance
  - Open loop gain is infinite
- This implies:
  - Input current at either input terminal is zero.
  - Under closed loop conditions, $V_1 = V_2$, $\Rightarrow$ both inputs will be at the same voltage. (super important!)



- Why can we say that $V_1 = V_2$? The amplifier cannot force this to happen by itself. We make this happen with negative feedback.
- Let's see how...

Operational Amplifier

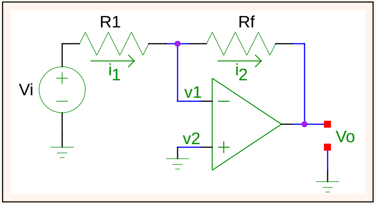
- Resistor R_f applies negative feedback to the op amp making the circuit operate *closed loop*. The value of R_f does not matter in this case, as $R_{in} = \infty$.



- Imagine if V_i goes up a little. Then V_o goes up until $V_1 = V_i$, then it stops. Equilibrium in a sense is reached. $V_i = V_o = V_1$.
- If V_i goes down a little, V_o goes down until it equals V_i then it stops.
- Let's look at some other op amp circuits.

Operational Amplifier

- We will now look at several op amp amplifier circuits. First up is the inverting amplifier. Let's find the circuit gain $A_v = \frac{V_o}{V_i}$ and the equation for V_o.



- Writing KCL at the inverting terminal:

$$\frac{V_i - V_1}{R_1} - \frac{V_1 - V_o}{R_f} = 0$$

$$R_1(V_1 - V_o) - R_f(V_i - V_1) = 0 \text{ ; cross mult., and since } V_1 = V_2 = 0$$

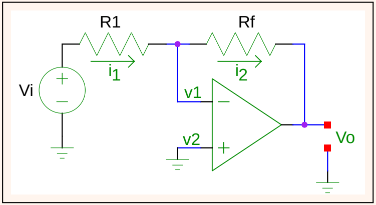
$$-R_1 V_o - R_f V_i = 0$$

$$\frac{V_o}{V_i} = -\frac{R_f}{R_1} \text{ ; the circuit voltage gain } A_v \text{ is: } -\frac{R_f}{R_1}$$

$$V_o = -V_i\left(\frac{R_f}{R_1}\right) \text{ ; output voltage has } -180^\circ \text{ phase shift}$$

Operational Amplifier

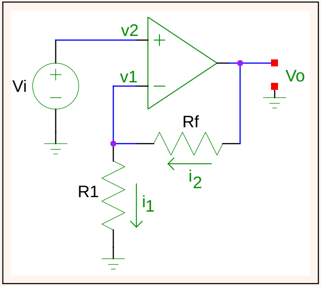
- Observations about the inverting amplifier:



- The minus sign in the gain equation tells us that the amplifier exhibits a $-180°$ phase shift.
- The gain is seen to be independent of the open loop gain and is only dependent on external components.
- Node V_1 is called the *virtual ground*. It is kept at $0V$ yet it is not connected to ground.
- Amplifier input resistance is R_1.
- Resistor R_f cannot be arbitrarily small. The op amp must be able to drive the V_1 node without excessive loading.

Operational Amplifier

- The non-inverting amplifier:



- Writing KCL at V_1 to find circuit gain and equation for V_o:

$$\frac{V_o - V_1}{R_f} = \frac{V_1}{R_1} \text{ ; } KCL \text{ @ } V_1, \text{ but } V_1 = V_2 = V_i, \text{ so:}$$

$$\frac{V_o - V_i}{R_f} = \frac{V_i}{R_1}$$

$$R_1(V_o - V_i) = R_f V_i$$

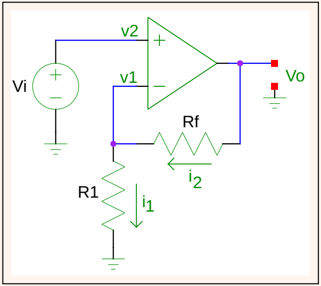
$$R_1 V_o - R_1 V_i = R_f V_i$$

$$R_1 V_o = R_f V_i + R_1 V_i$$

$$V_o = V_i\left(\frac{R_f + R_1}{R_1}\right) = V_i\left(1 + \frac{R_f}{R_1}\right) \text{ ; and } A_v = \left(1 + \frac{R_f}{R_1}\right)$$

Operational Amplifier

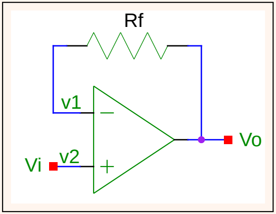
- Observations about the non-inverting amplifier:



- Amplifier input resistance is ∞.
- A positive gain equation tells us that the amplifier does not introduce a phase change.
- The gain is independent of open loop gain and dependent only on external components.
- There is no *virtual ground*. However, $V_1 = V_2$ as the loop is closed.
- Resistors R_f and R_1 must still be chosen appropriately.

Operational Amplifier

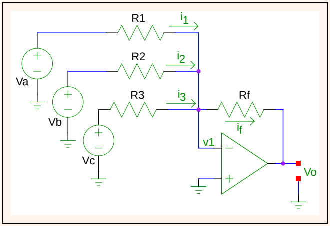
- The degenerate case of the non-inverting amplifier is when $R1 = \infty$ and $R_f = 0$. In this case $A_v = 1$. R_f could be any practical value.



- This is called a voltage follower or unity-gain buffer.
- This amplifier has infinite power and current gain and unity voltage gain.

Operational Amplifier

- The summing inverting amplifier:



- Writing KCL at V_1 to find the equation for V_o:

  $i_f = i_1 + i_2 + i_3$ *; where*

  $$i_1 = \frac{V_a - V_1}{R_1},\ i_2 = \frac{V_b - V_1}{R_2},\ i_3 = \frac{V_c - V_1}{R_3},\ \textit{and}\ i_f = \frac{V_1 - V_o}{R_f}$$

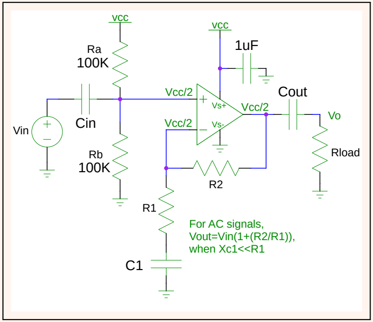
- In closed loop, $V_1 = 0$, which results in:

  $$\frac{V_a}{R_1} + \frac{V_b}{R_2} + \frac{V_c}{R_3} = -\frac{V_o}{R_f}\ \textit{thus:}$$

  $$V_o = -\left[V_a\left(\frac{R_f}{R_1}\right) + V_b\left(\frac{R_f}{R_2}\right) + V_c\left(\frac{R_f}{R_3}\right)\right]$$ *; a weighted sum of the inputs*

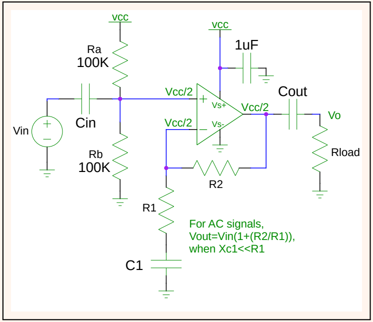
Operational Amplifier

- So far we have used a power supply with both positive and negative potentials. Sometimes, there is only a single polarity supply source. We will need extra components to implement *single-supply* circuits.
- The additional circuitry biases the op amp output to $0.5V_{cc}$. This allows for maximum input and output voltage swing for a given supply voltage.



Operational Amplifier

- R_a and R_b bias the non-inverting input to $V_{cc}/2$. Op amp inputs and outputs are all at $V_{cc}/2$!
- The input signal is capacitively coupled to the non-inverting input.
- Power supply noise rejection is missing. Noise on V_{cc} will be coupled to the non-inverting input.
- If the op amp current consumption causes a change on V_{cc}, a feedback loop would be formed possibly causing instability or oscillations.



Operational Amplifier

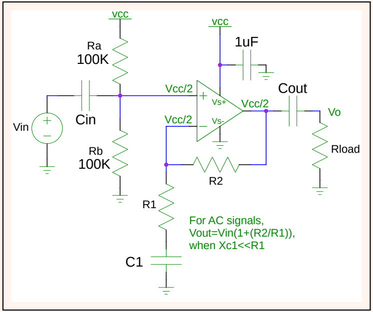
- Several bandwidth breakpoints have been created. The choice of the capacitors depends on the desired bandwidth of the amplifier.

$$BW_1 = \frac{1}{2\pi(R_a||R_b)C_{in}} \;;\; \textit{high-pass}$$

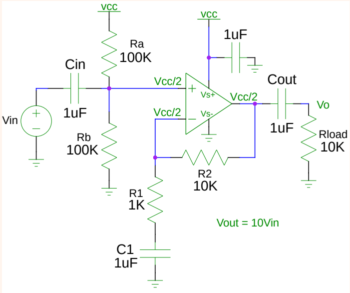
$$BW_2 = \frac{1}{2\pi R_1 C_1} \;;\; \textit{high-pass}$$

$$BW_3 = \frac{1}{2\pi R_{load} C_{out}} \;;\; \textit{high-pass}$$

- With: $R_a = R_b = 100K$, $R_2 = 10K$, $R_1 = 1K$, $C_1 = C_2 = C_3 = 1uF$
$BW_1 = 3.18hz$, $BW_2 = 159hz$ (dominant), $BW_3 = 16hz$



Operational Amplifier




```
.title opamp_single_supply.sp

.include LM358.subckt
Vin in gnd ac=1m ; for small signal response

Vcc    vcc        gnd        12v   ; single supply
*.subckt LM358 IN+ IN- VCC VEE OUT   ; LM358 pin order
XOPAMP in_pos in_neg vcc gnd opamp_out LM358 ; OPAMP

Cin    in          in_pos    1uF ;input coupling cap
Ra     Vcc         in_pos    100K ;biasing resistor
Rb     in_pos         gnd    100K ;biasing resistor

R1     in_neg     cap_tie    1K  ;gain setting resistor
C1     cap_tie        gnd    1uF ;DC blocking cap
Rf     opamp_out  in_neg     10K ;gain setting resistor

Cout   opamp_out      out    1uF ;output coupling cap
Rload        out      gnd    10K ;lightly loaded

.control
  destroy all ; remove old plots
* printing and color options
  set hcopydevtype=postscript
  set hcopypscolor=true
  set color0=rgb:f/f/f
  set color1=rgb:0/0/0
* small signal analysis
  ac dec 10 1 1meg ; 10 pts per decade, 1 hz-1mhz
  plot 20*log10(vm(out)/vm(in)) ylabel '20*log(v(out)/v(in))'
.endc
.end
```

Operational Amplifier

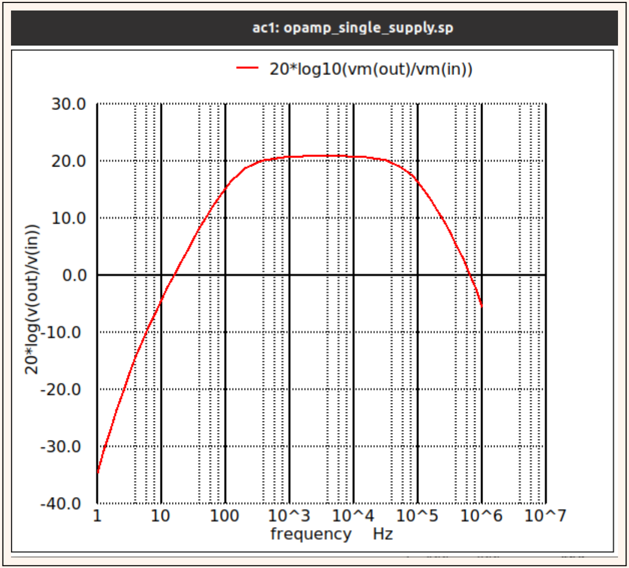


Figure: Gain of 10 op amp amplifier with all caps 1uF

Operational Amplifier

- Modifying the amplifier to decouple the tap point on the voltage divider restores some of the power supply noise rejection. The capacitor (C_{byp}) needs to be large enough to set the -3dB bandwidth low enough to be effective for the lowest frequencies anticipated to be on V_{cc}. A rule of thumb is for R_a,R_b, and C_{byp} to set a pole roughly $1/10$ the -3dB pole for $R1$,$C1$ or C_{in},R_{in}.
- Gain resistors were changed to offset input bias current errors.

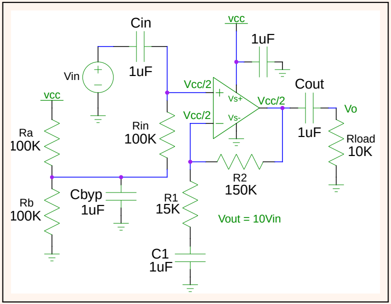


Figure: Non-inverting op amp amplifier with decoupled bias

Operational Amplifier

- These same technique can be applied to the inverting amplifier.
- The input impedance is 5k ohms.
- Gain resistors were adjusted to offset input bias current errors.

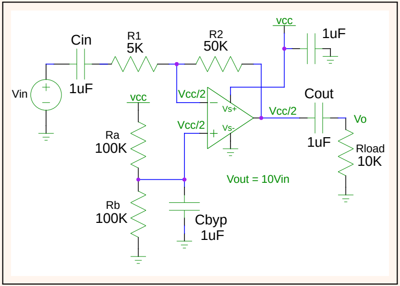


Figure: Inverting op amp amplifier with decoupled bias

Operational Amplifier

- Split power rails can be synthesized by several means.
- One of the easiest is the TI TLE2426.

TLE2426, TLE2426Y
THE "RAIL SPLITTER"
PRECISION VIRTUAL GROUND

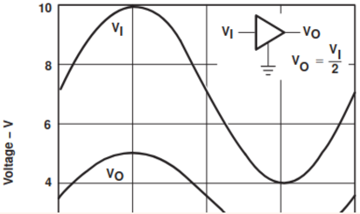
SLOS098D – AUGUST 1991 – REVISED MAY 1998

- **1/2 V_I Virtual Ground for Analog Systems**
- **Self-Contained 3-terminal TO-226AA Package**
- **Micropower Operation . . . 170 µA Typ, V_I = 5 V**
- **Wide V_I Range . . . 4 V to 40 V**
- **High Output-Current Capability**
  - **Source . . . 20 mA Typ**
  - **Sink . . . 20 mA Typ**
- **Excellent Output Regulation**
  - **−45 µV Typ at I_O = 0 to −10 mA**
  - **+15 µV Typ at I_O = 0 to +10 mA**
- **Low-Impedance Output . . . 0.0075 Ω Typ**
- **Noise Reduction Pin (D, JG, and P Packages Only)**

description

In signal-conditioning applications utilizing a single power source, a reference voltage equal to one-half the supply voltage is required for termination of all analog signal grounds. Texas Instruments presents a precision virtual ground whose output voltage is always equal to one-half the input voltage, the TLE2426 "rail splitter."

INPUT/OUTPUT TRANSFER CHARACTERISTICS



Operational Amplifier

- You can also "roll your own" rail splitter with an op amp.
- This should look familiar!