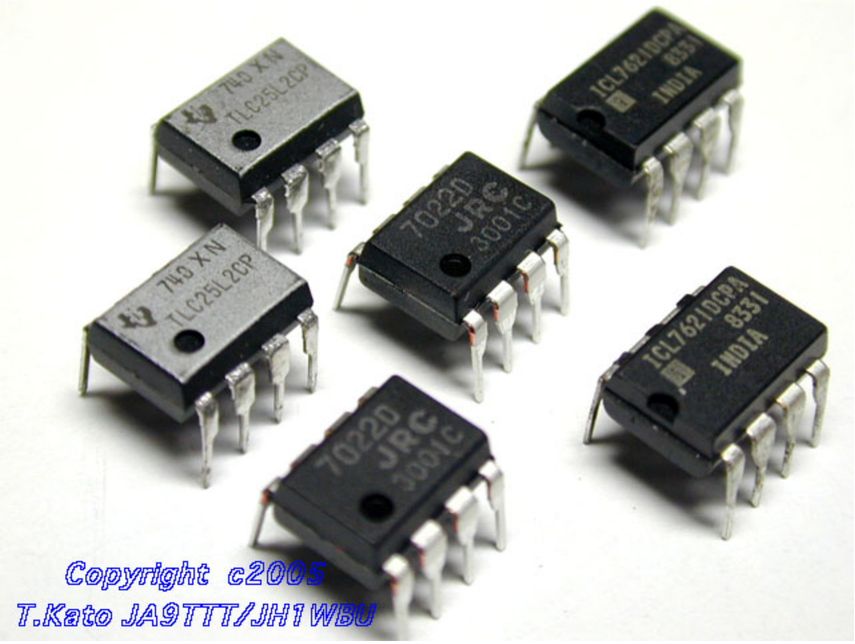
Tom Murphy, UCSD
http://physics.ucsd.edu/~tmurphy/phys121/phys121.html



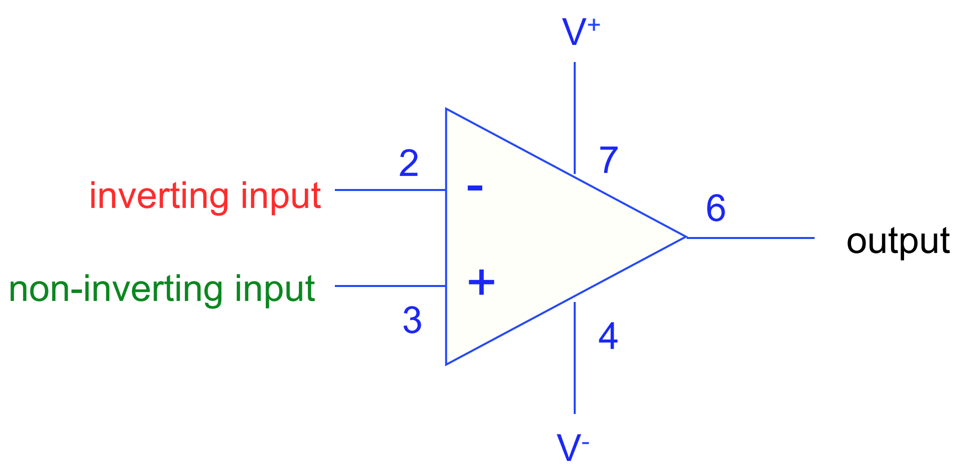
Operational Amplifiers

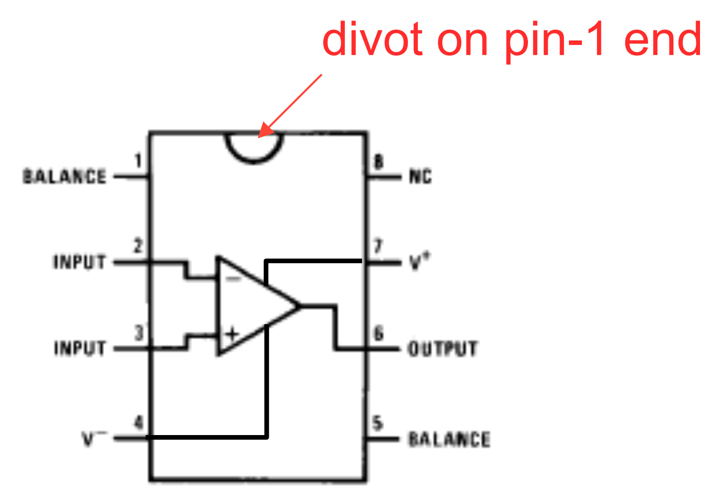
Magic Rules

Application Examples

Op-Amp Introduction

- Op-amps (amplifiers/buffers in general) are drawn as a triangle in a circuit schematic
- There are two inputs
  - inverting and non-inverting
- And one output
- Also power connections (note no explicit ground)

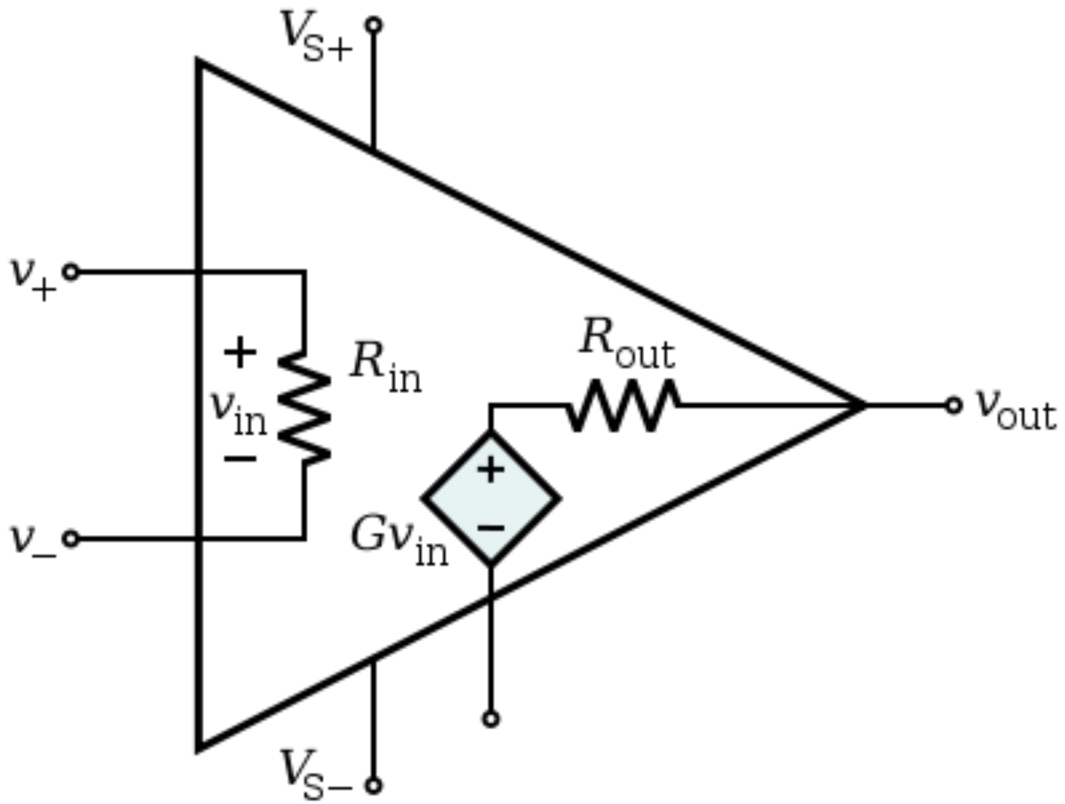




The ideal op-amp

- Infinite voltage gain
  - a voltage difference at the two inputs is magnified infinitely
  - in truth, something like 200,000
  - means difference between + terminal and - terminal is amplified by 200,000!
- Infinite input impedance
  - no current flows into inputs
  - in truth, about 10^{12} Ω for FET input op-amps
- Zero output impedance
  - rock-solid independent of load
  - roughly true up to current maximum (usually 5–25 mA)
- Infinitely fast (infinite bandwidth)
  - in truth, limited to few MHz range
  - slew rate limited to 0.5–20 V/μs

op amp: modello

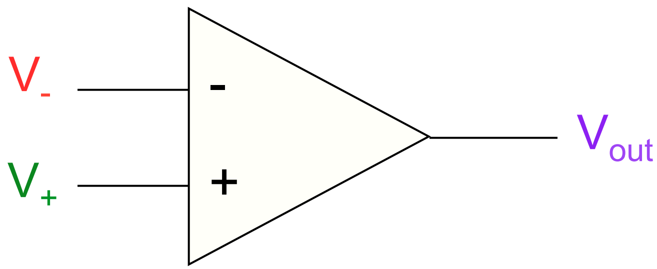


Op-amp without feedback

- The internal op-amp formula is:

$$V_{out} = gain \times (V_+ - V_-)$$

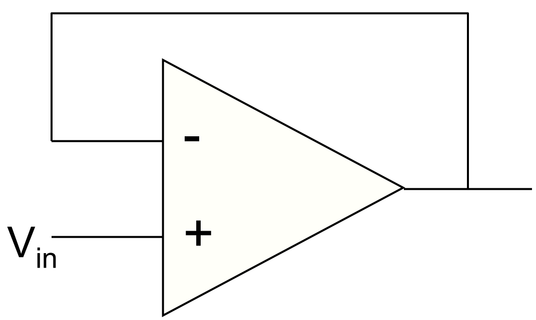
- So if V_+ is greater than V_-, the output goes positive
- If V_- is greater than V_+, the output goes negative



- A gain of 200,000 makes this device (as illustrated here) practically useless

Infinite Gain in negative feedback

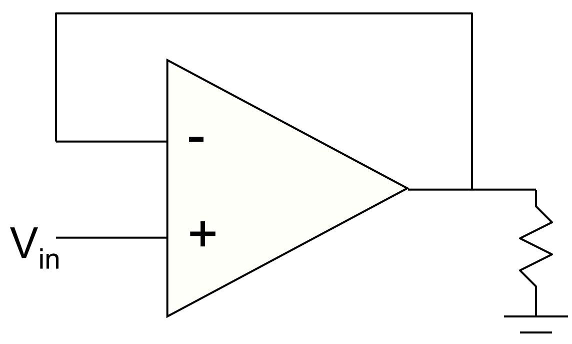
- Infinite gain would be useless except in the self-regulated negative feedback regime
  - negative feedback seems bad, and positive good—but in electronics positive feedback means runaway or oscillation, and negative feedback leads to stability
- Imagine hooking the output to the inverting terminal:
- If the output is less than V_{in}, it shoots positive
- If the output is greater than V_{in}, it shoots negative
  - result is that output quickly forces itself to be exactly V_{in}



negative feedback loop

Even under load

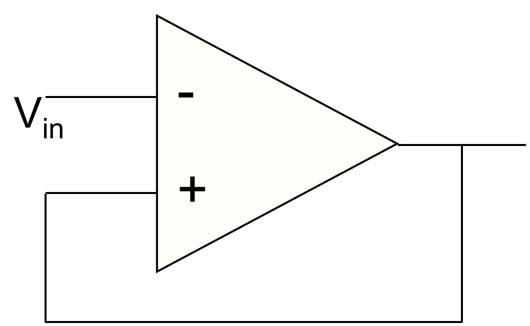
- Even if we load the output (which as pictured wants to drag the output to ground)…
  - the op-amp will do everything it can within its current limitations to drive the output until the inverting input reaches V_{in}
  - negative feedback makes it self-correcting
  - in this case, the op-amp drives (or pulls, if V_{in} is negative) a current through the load until the output equals V_{in}
  - so what we have here is a buffer: can apply V_{in} to a load without burdening the source of V_{in} with *any* current!



Important note: op-amp output terminal sources/sinks current at will: not like inputs that have no current flow

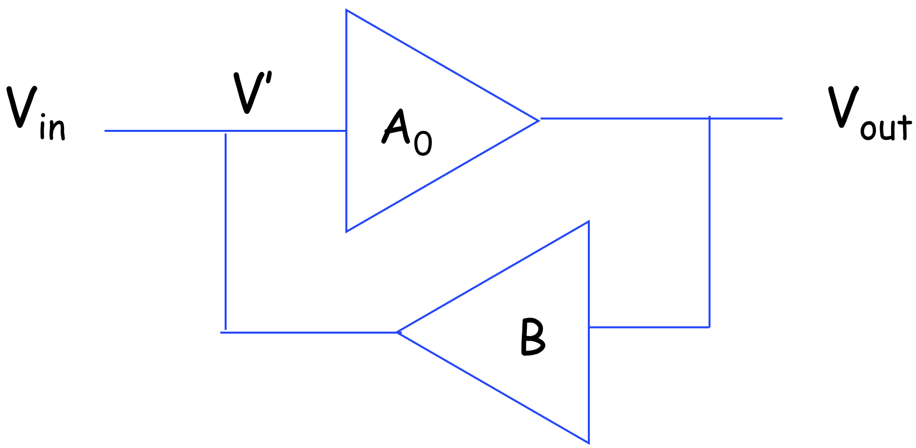
Positive feedback pathology

- In the configuration below, if the + input is even a smidge higher than V_{in}, the output goes way positive
- This makes the + terminal even *more* positive than V_{in}, making the situation worse
- This system will immediately "rail" at the supply voltage
  - could rail either direction, depending on initial offset



positive feedback: BAD

feedback



$$A = \frac{V_{out}}{V_{in}}$$

$$V_{out} = A_o V'$$

$$V' = V_{in} + \beta V_{out}$$

$$V_{out} = A_o(V_{in} + \beta V_{out})$$

$$V_{out}(1 - \beta A_o) = A_o V_{in}$$

$$\frac{V_{out}}{V_{in}} = \frac{A_o}{(1 - \beta A_o})$$

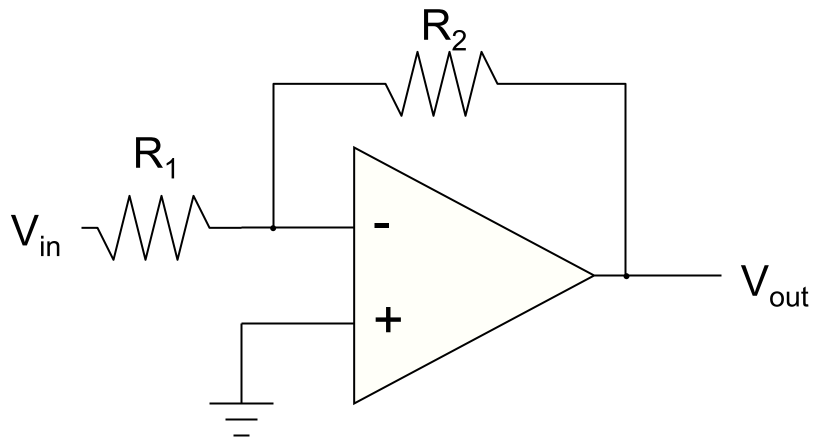
$$A = \frac{A_o}{(1 - \beta A_o})$$

$$A = \frac{A_o}{(1 + \beta A_o}) \sim \frac{1}{\beta}$$

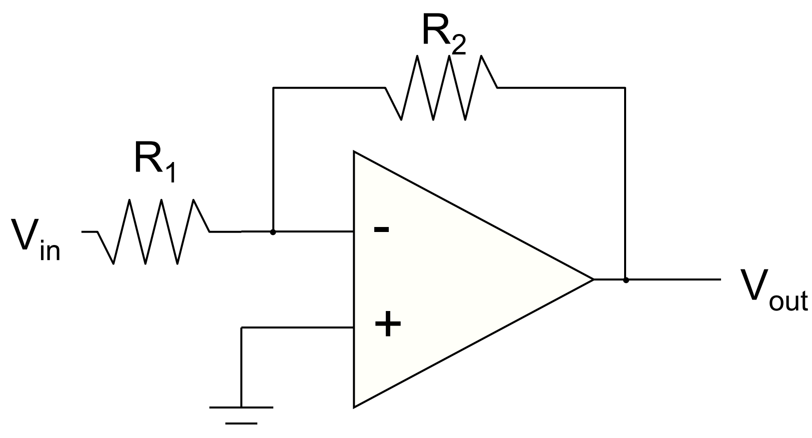
Op-Amp "Golden Rules"

- When an op-amp is configured in *any* negative-feedback arrangement, it will obey the following two rules:
  - The inputs to the op-amp draw or source no current (true whether negative feedback or not)
  - The op-amp output will do whatever it can (within its limitations) to make the voltage difference between the two inputs zero

Inverting amplifier example

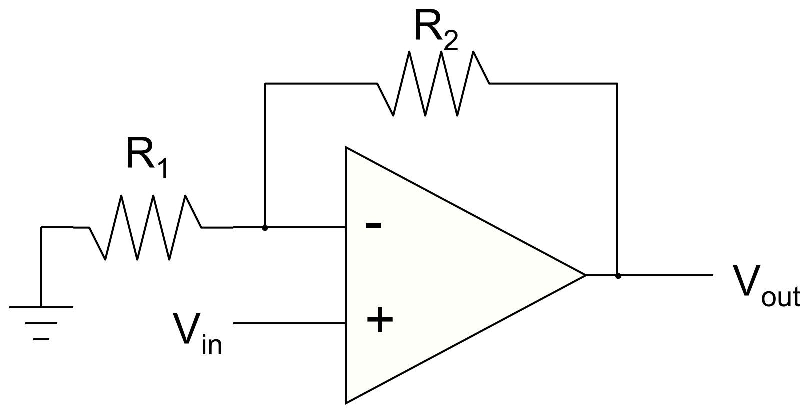


Inverting amplifier example

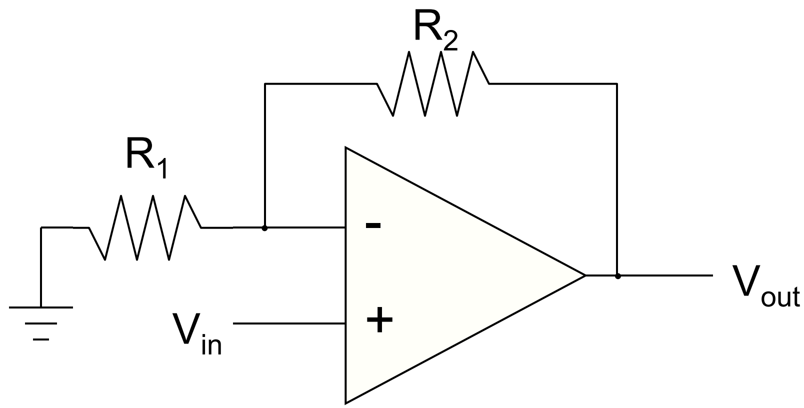


- Applying the rules: - terminal at "virtual ground"
  - so current through R_1 is $I_f = V_{in}/R_1$
- Current does not flow into op-amp (one of our rules)
  - so the current through R_1 must go through R_2
  - voltage drop across R_2 is then $I_f R_2 = V_{in} \times (R_2/R_1)$
- So $V_{out} = 0 - V_{in} \times (R_2/R_1) = -V_{in} \times (R_2/R_1)$
- Thus we amplify V_{in} by factor $-R_2/R_1$
  - negative sign earns title "inverting" amplifier
- Current is *drawn into* op-amp output terminal

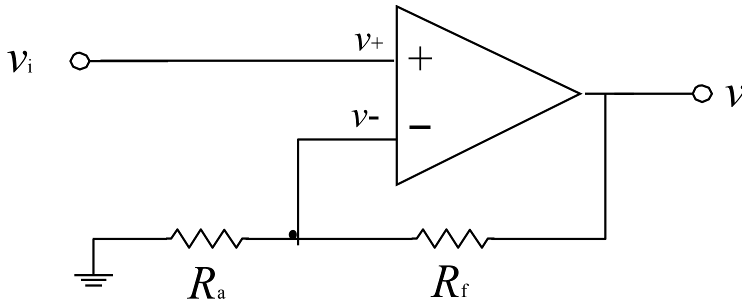
Non-inverting Amplifier



Non-inverting Amplifier

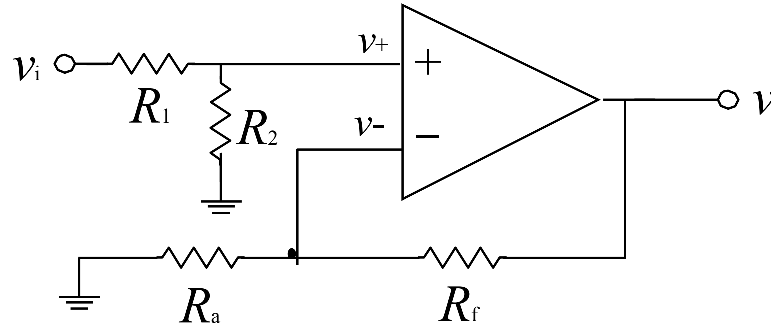


- Now neg. terminal held at V_{in}
  - so current through R_1 is $I_f = V_{in}/R_1$ (to left, into ground)
- This current cannot come from op-amp input
  - so comes through R_2 (delivered from op-amp output)
  - voltage drop across R_2 is $I_f R_2 = V_{in}\times(R_2/R_1)$
  - so that output is higher than neg. input terminal by $V_{in}\times(R_2/R_1)$
  - $V_{out} = V_{in} + V_{in}\times(R_2/R_1) = V_{in}\times(1 + R_2/R_1)$
  - thus gain is $(1 + R_2/R_1)$, and is positive
- Current is sourced from op-amp output in this example



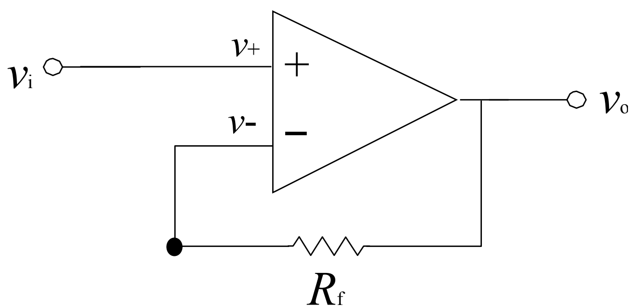
Noninverting amplifier

$$v_o = \left(1 + \frac{R_f}{R_a}\right) v_i$$



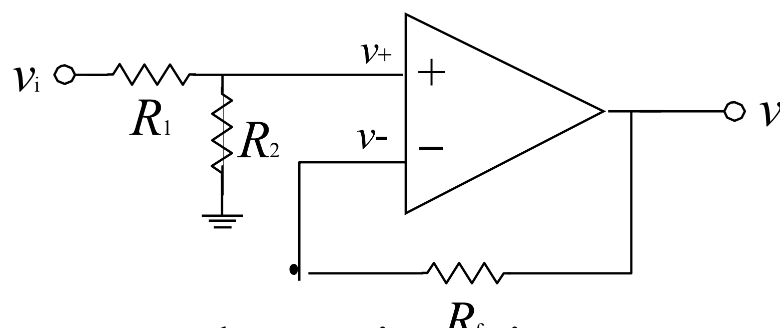
Noninverting input with voltage divider

$$v_o = \left(1 + \frac{R_f}{R_a}\right)\left(\frac{R_2}{R_1 + R_2}\right) v_i$$



Voltage follower

$$v_o = v_i$$

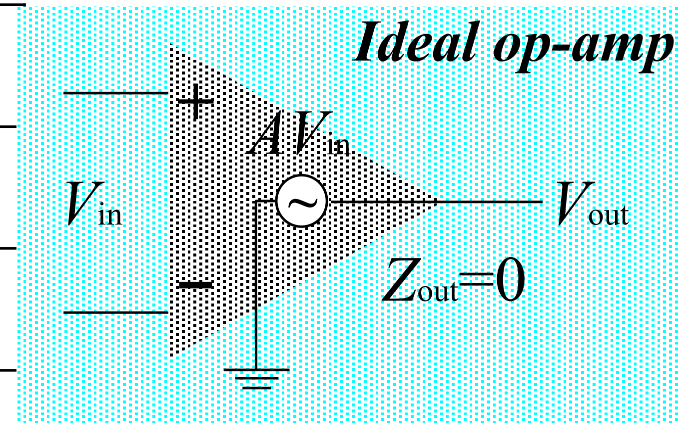


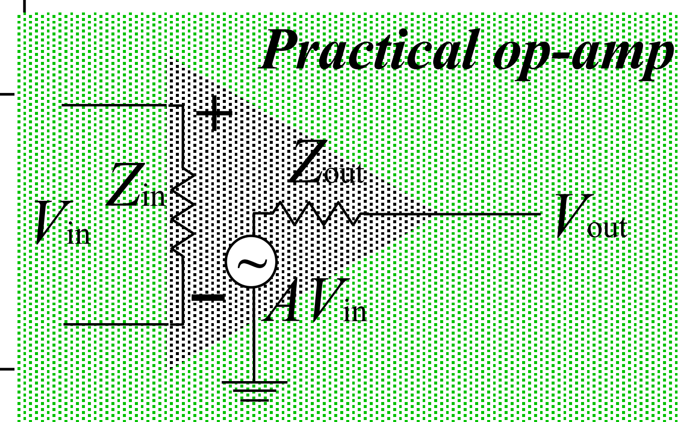
Less than unity gain

$$v_o = \frac{R_2}{R_1 + R_2} v_i$$

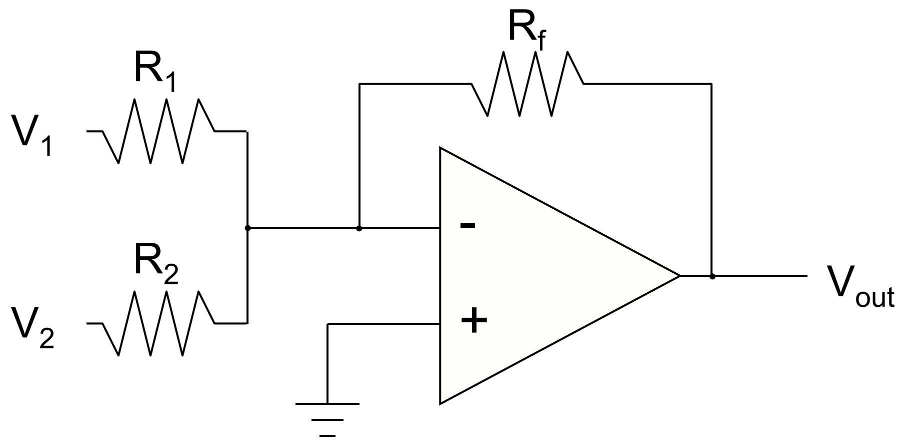
Ideal Vs Practical Op-Amp

	Ideal	Practical
Open Loop gain A	$\propto$	10^5
Bandwidth BW	$\propto$	10-100Hz
Input Impedance Z_{in}	$\propto$	>1MΩ
Output Impedance Z_{out}	0 Ω	10-100 Ω
Output Voltage V_{out}	Depends only on $V_d = (V_+ - V_-)$ Differential mode signal	Depends slightly on average input $V_c = (V_+ + V_-)/2$ Common-Mode signal
CMRR	$\propto$	10-100dB



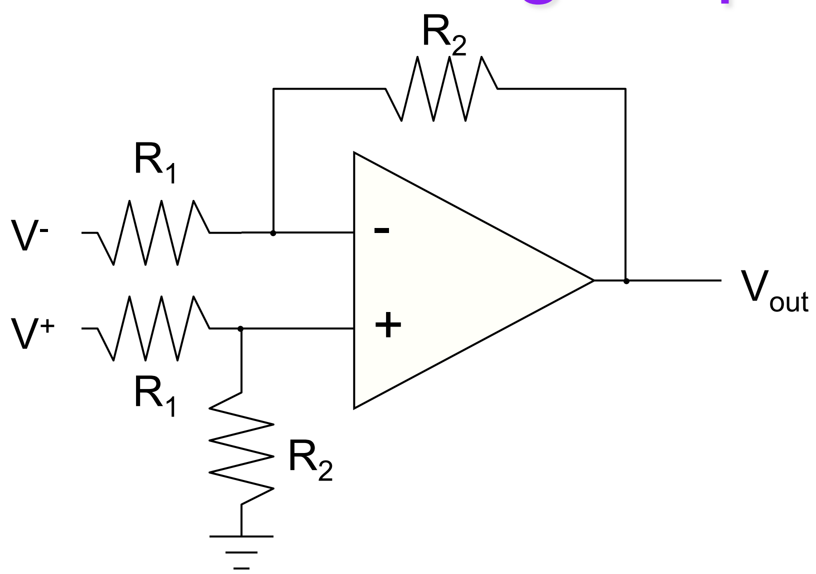


Summing Amplifier



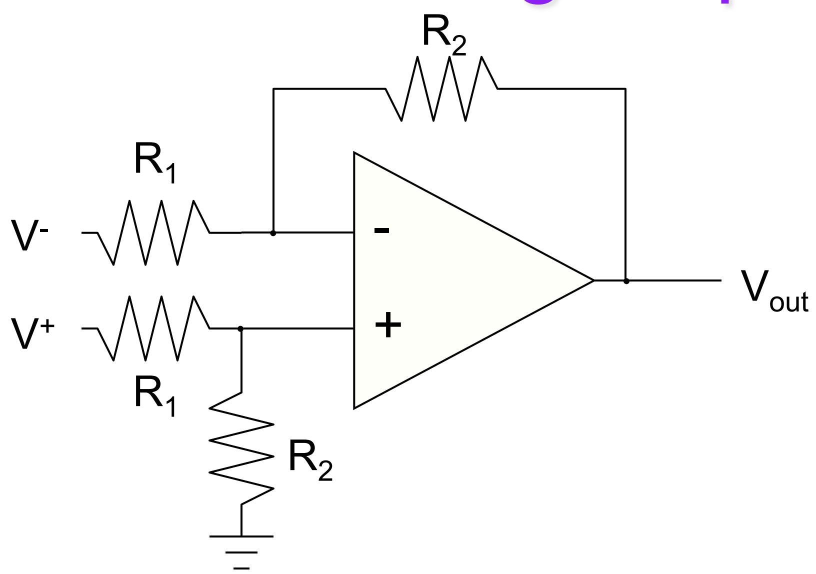
- Much like the inverting amplifier, but with two input voltages
  - inverting input still held at virtual ground
  - I_1 and I_2 are added together to run through R_f
  - so we get the (inverted) sum: $V_{out} = -R_f \times (V_1/R_1 + V_2/R_2)$
    - if $R_2 = R_1$, we get a sum proportional to $(V_1 + V_2)$
- Can have any number of summing inputs
  - we'll make our D/A converter this way

Differencing Amplifier



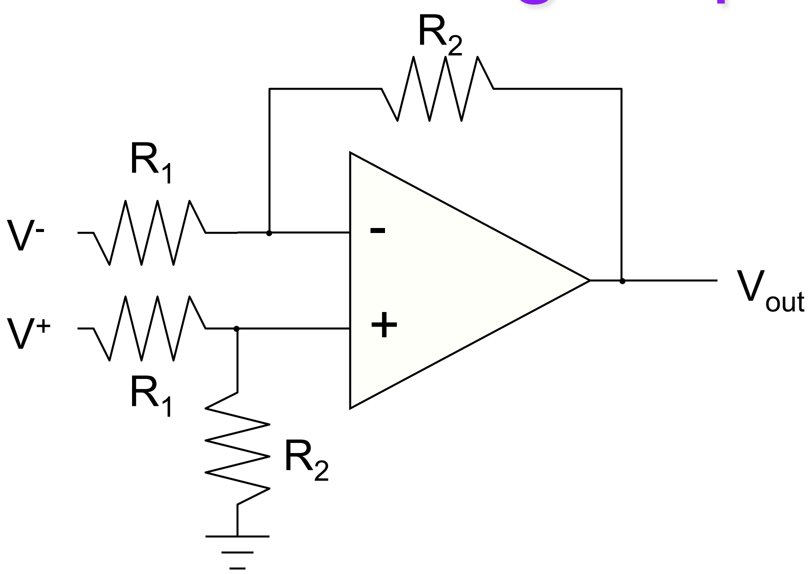
- The non-inverting input is a simple voltage divider:

Differencing Amplifier



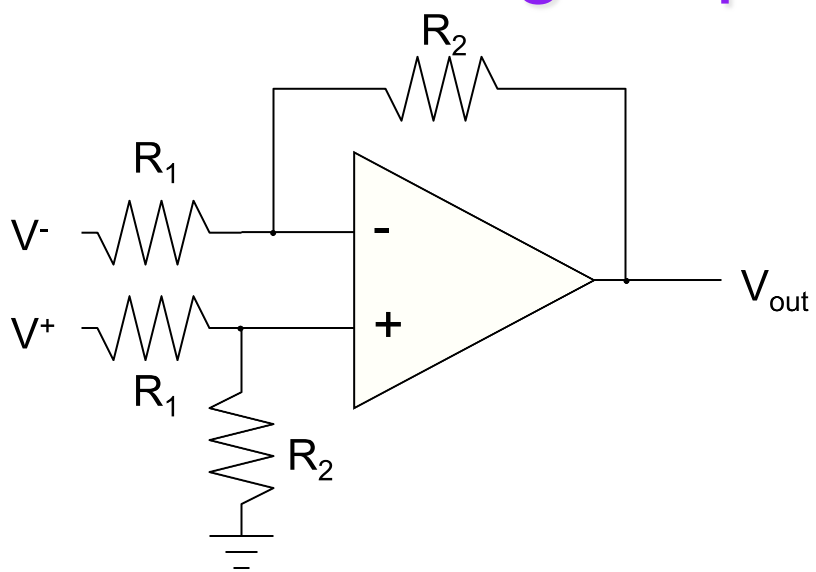
- The non-inverting input is a simple voltage divider:
  - $V_{node} = V^{+}R_2/(R_1 + R_2)$

Differencing Amplifier



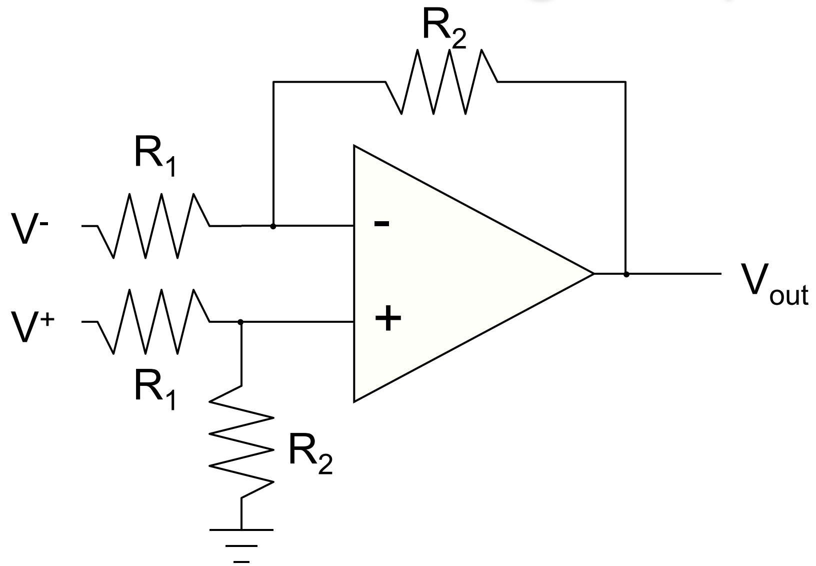
- The non-inverting input is a simple voltage divider:
  - $V_{node} = V^{+}R_2/(R_1 + R_2)$
- So $I_f = (V^{-} - V_{node})/R_1$

Differencing Amplifier



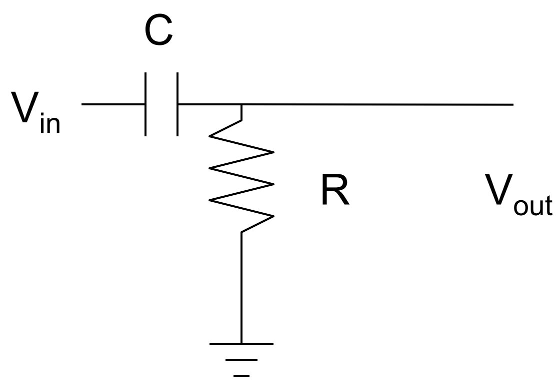
- The non-inverting input is a simple voltage divider:
  - $V_{node} = V^{+}R_2/(R_1 + R_2)$
- So $I_f = (V^{-} - V_{node})/R_1$
  - $V_{out} = V_{node} - I_fR_2 = V^{+}(1 + R_2/R_1)(R_2/(R_1 + R_2)) - V^{-}(R_2/R_1)$

Differencing Amplifier



- The non-inverting input is a simple voltage divider:
  - $V_{node} = V^+R_2/(R_1 + R_2)$
- So $I_f = (V^- - V_{node})/R_1$
  - $V_{out} = V_{node} - I_fR_2 = V^+(1 + R_2/R_1)(R_2/(R_1 + R_2)) - V^-(R_2/R_1)$
  - so $V_{out} = (R_2/R_1)(V^+ - V^-)$

Differentiator (high-pass)



$$Q = CV$$

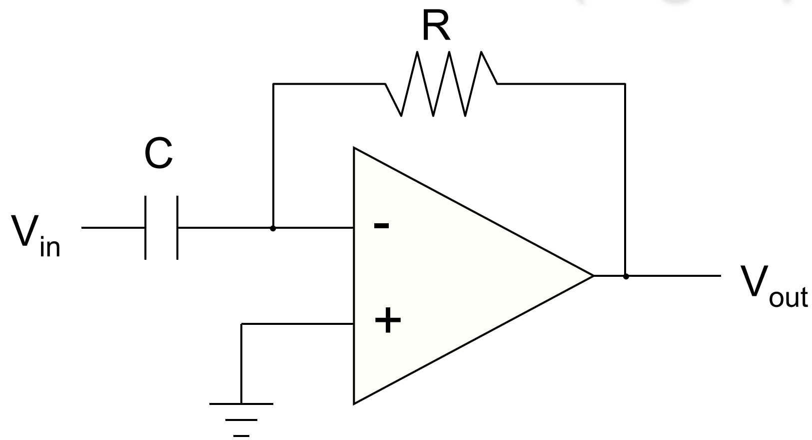
$$I = \frac{dQ}{dt} = C\frac{dV}{dt}$$

$$I = C\frac{d}{dt}(V_{in} - V_{out}) = \frac{V_{out}}{R}$$

$$\frac{dV_{out}}{dt} \ll \frac{dV_{in}}{dt} \qquad C\frac{dV_{in}}{dt} = \frac{V_{out}}{R}$$

$$V_{out} = RC\frac{dV_{in}}{dt}$$

Differentiator (high-pass)



- For a capacitor

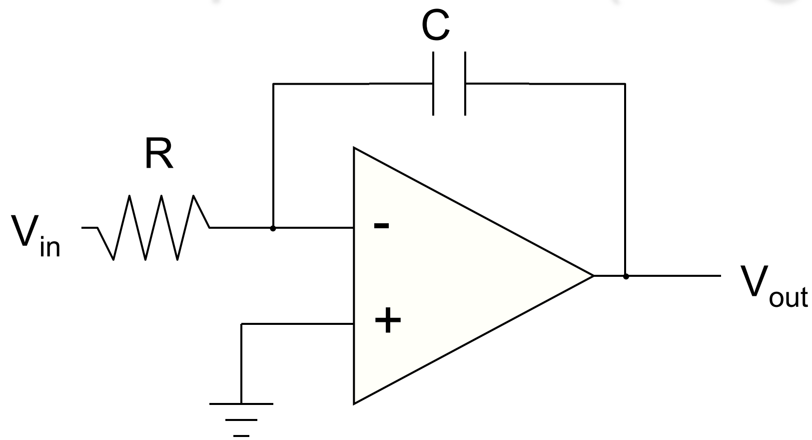
$$Q = CV$$

$$I = \frac{dQ}{dt} = C\frac{dV}{dt}$$

$$V_{out} = -I_{cap}R = -RC\frac{dV}{dt}$$

- So we have a differentiator, or high-pass filter

Low-pass filter (integrator)



$$Q = CV$$

$$I = \frac{dQ}{dt} = C\frac{dV}{dt}$$

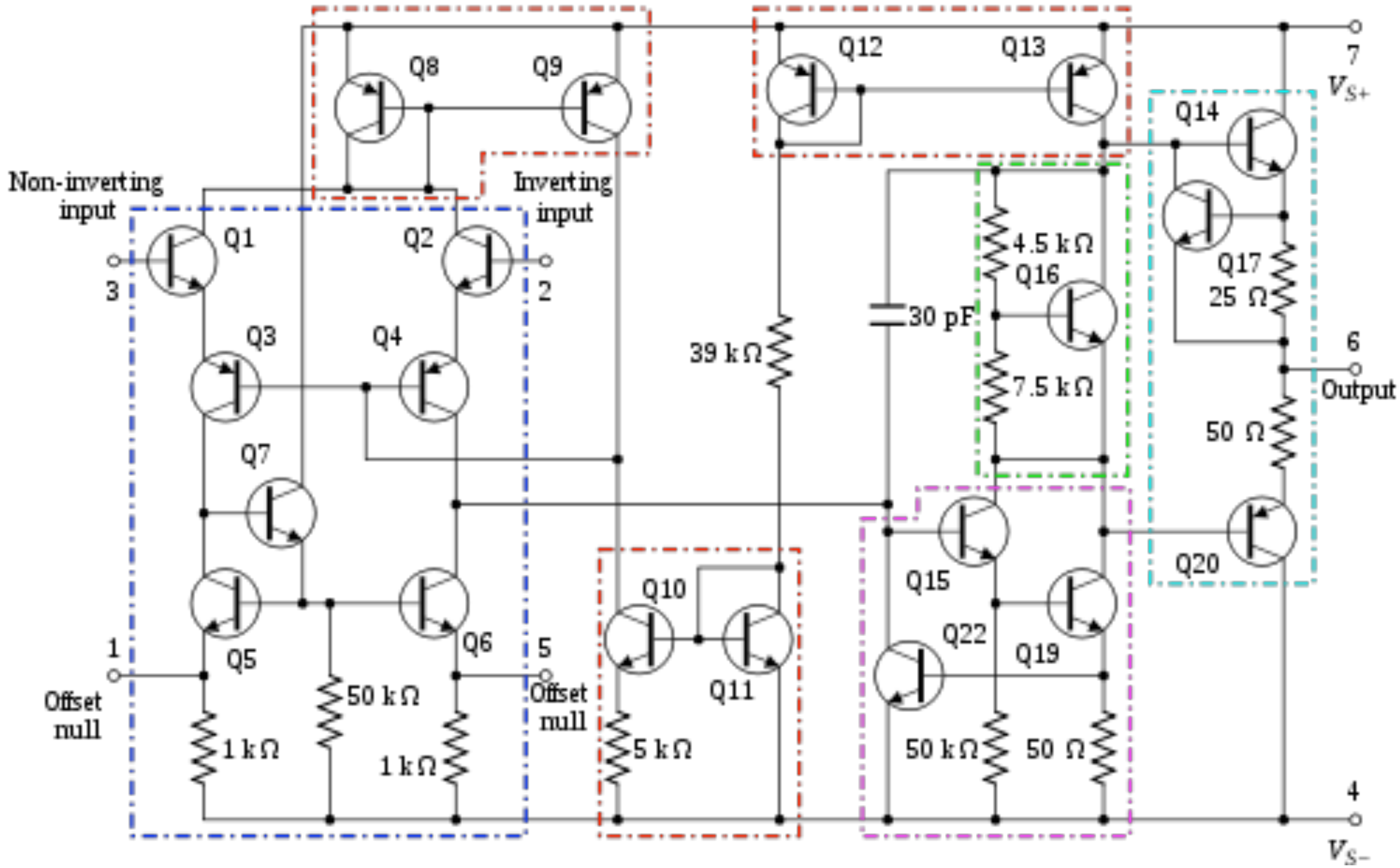
- $I_f = V_{in}/R$, so $C \cdot dV_{cap}/dt = V_{in}/R$
  - and since left side of capacitor is at virtual ground:

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

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

  - and therefore we have an integrator (low pass)

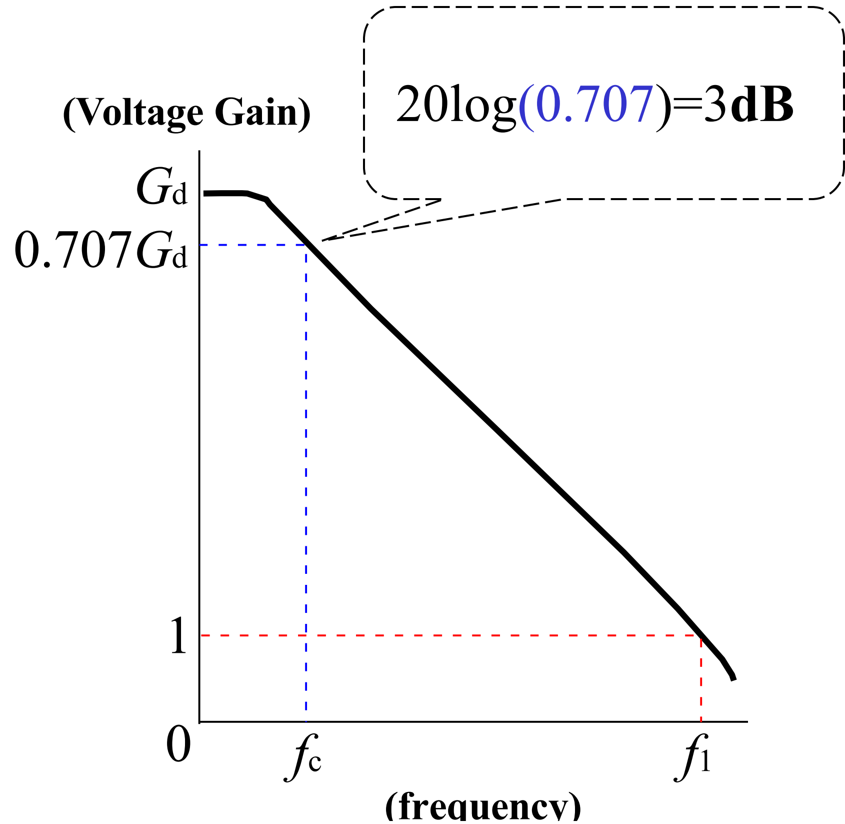
esempio: 741



Q8
Q9
Q12
Q13
7
V_{S+}
Q14
Non-inverting input
Inverting input
Q1
Q2
3
2
Q17
25 Ω
4.5 kΩ
Q16
Q3
Q4
30 pF
39 kΩ
6
Output
7.5 kΩ
Q7
50 Ω
Q20
Q15
Q10
Q22
Q19
1
Q5
Q6
5
Offset null
50 kΩ
Offset null
Q11
1 kΩ
1 kΩ
5 kΩ
50 kΩ
50 Ω
4
V_{S-}

Frequency-Gain Relation

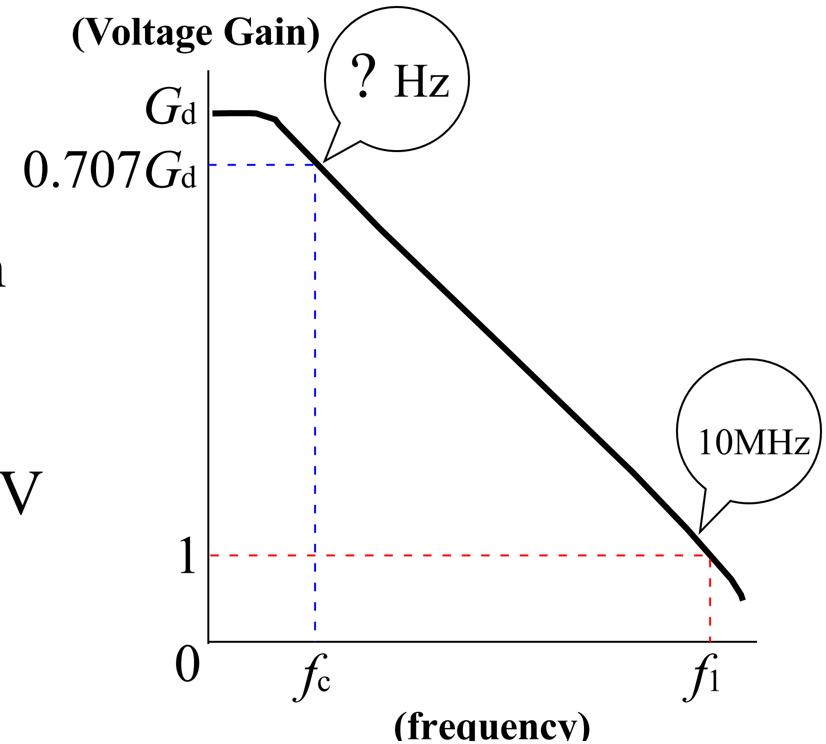
- Ideally, signals are amplified from DC to the highest AC frequency
- Practically, bandwidth is limited
- 741 family op-amp have an limit bandwidth of few KHz.
- Unity Gain frequency f_1: the gain at unity
- Cutoff frequency f_c: the gain drop by 3dB from dc gain G_d



$$\text{GB Product}: f_1 = G_d f_c$$

GB Product

Example: Determine the cutoff frequency of an op-amp having a unit gain frequency f_1 = 10 MHz and voltage differential gain G_d = 20**V**/m**V**



Sol:

Since f_1 = 10 MHz

By using GB production equation

$$f_1 = G_d f_c$$

$$f_c = f_1 / G_d = 10 \text{ MHz} / 20 \text{ V/mV}$$

$$= 10 \times 10^6 / 20 \times 10^3$$

$$= 500 \text{ Hz}$$

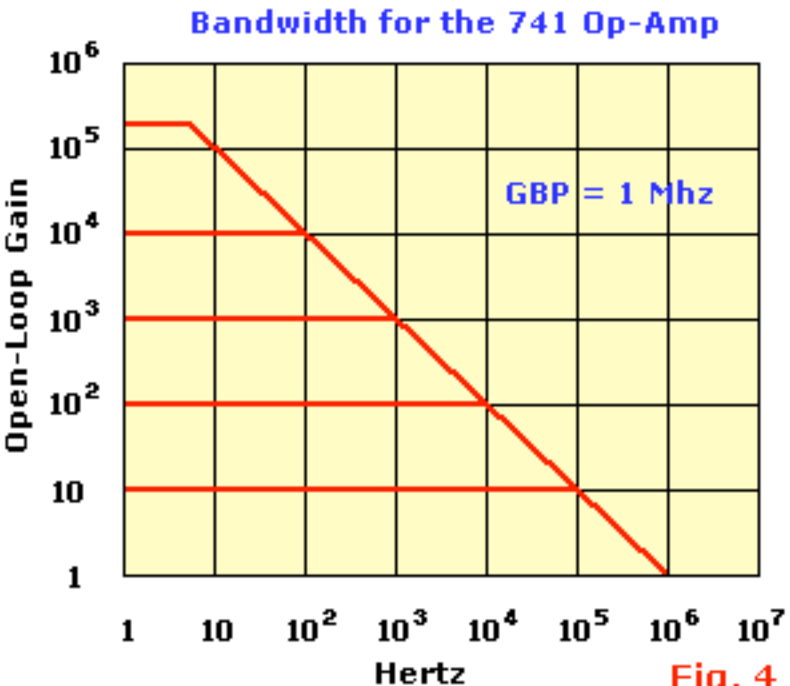


Fig. 4

Gain-Bandwidth product: $GBP = A_o\ BW$