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We will spend the next two weeks on opamps ("operational amplifiers").

An opamp is a high-gain differential amplifier with very high input impedance. It is nearly always used with negative feedback. (Negative feedback means, for example, if my car starts to veer toward the right (left), I turn the steering wheel to the left (right) to compensate.)

Most of what you need to know about analyzing opamp circuits can be summed up in two Golden Rules. We will see later why the rules work. For now, get comfortable with using them.

Rule #0 (standard disclaimers) If negative feedback is present (especially at DC) and the output is not saturated (i.e. pegged at the $\pm V_{supply}$ rails), then

Rule #1 The output does whatever is needed to make $V_{in}^{+} - V_{in}^{-} = 0$.

Rule #2 The inputs draw negligible current.

#2 is a consequence of high input impedance and doesn't depend on #0.

#1 is a consequence of high gain, if #0 is met.

Q: Why do you need amplifiers, anyway?

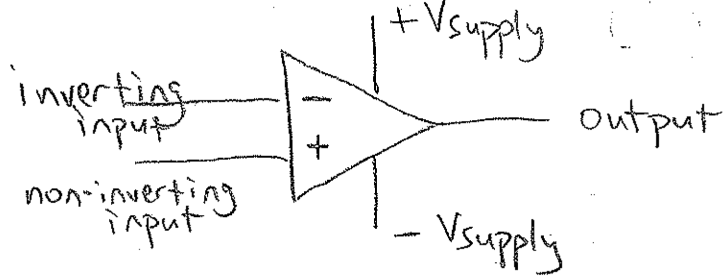
A: Circuits having only passive components have no power gain. They can not drive your massive stereo speakers from your wimpy MP3 player.

An amplifier can turn a weak source into a strong source — e.g. serving as a go-between for a source whose Z_{OUT} is not small enough to drive the desired load's Z_{IN} without drooping.

Feedback provides an easy way to do all sorts of handy tasks: integration, differentiation, logarithms, summing several input voltages, scaling input voltage by a factor larger than 1, ...

Q: Why opamps?

Opamps are building blocks that allow you to build circuits whose performance depends more on the chosen values of a few passive components than on the details of the opamp itself. They will become one of your favorite LEGO bricks. Can be plugged in in many different configurations.



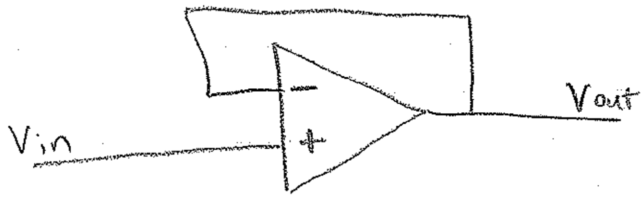
$$V_{OUT} = G \cdot (V_{IN+} - V_{IN-})$$

$$G \gg 1 \quad (\text{e.g.} \sim 10^6)$$

± Vsupply is external power source, e.g. ±15 volts
(depends on opamp model, available voltages, ...)

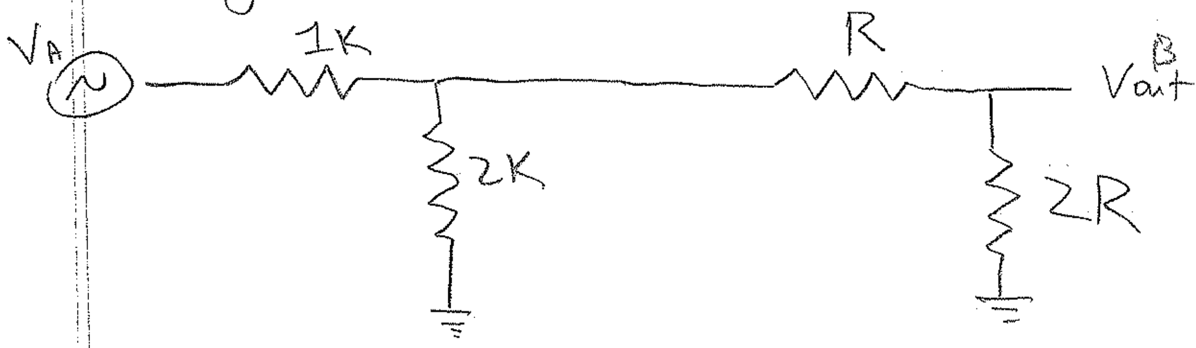
output can not go past the rails, e.g. for ±15 V supply, Vout cannot exceed ≈ ±13 V
(some opamps boast "rail-to-rail" operation)

± Vsupply connections are usually implicit on schematic (i.e. you seldom draw them) "follower" (a.k.a. "buffer")



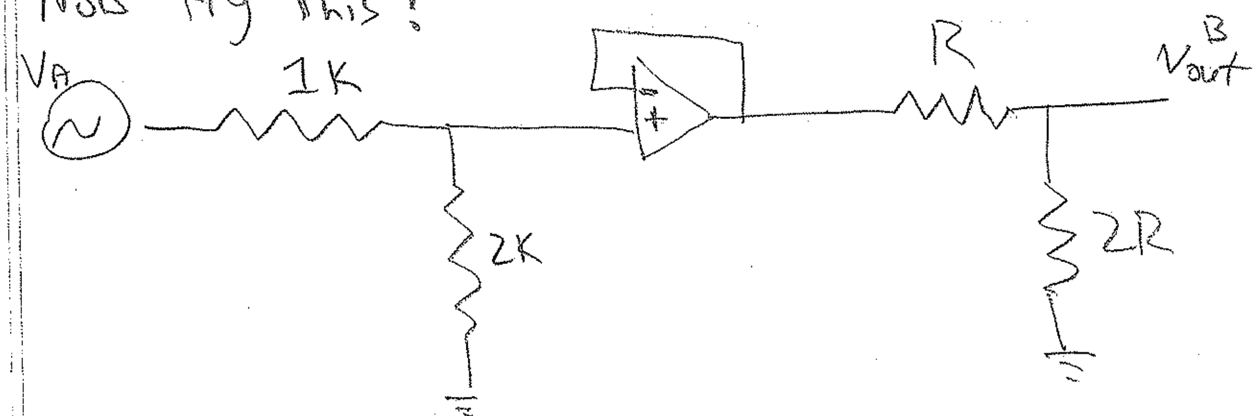
Rule #1 implies $V_{out} = V_{in}$.
Rule #2 implies $R_{IN} = \infty$ (ideally, anyway)

Do you remember these two circuits?



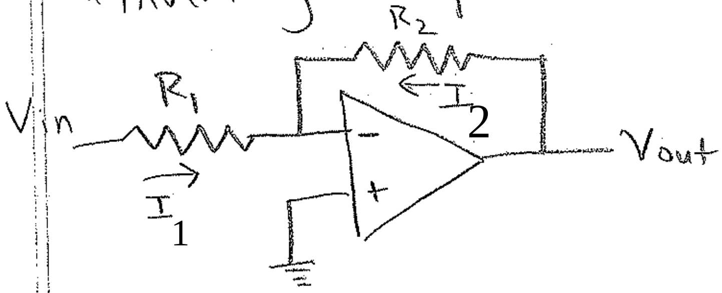
Recall $R = 100K \Rightarrow$ light load, negligible droop
$R = 1K \Rightarrow$ heavy load, substantial droop

Now try this!



Now A sees $R_{IN} \ggg 1K$ and B sees $R_{OUT} \lll 1K$.

"inverting amplifier"



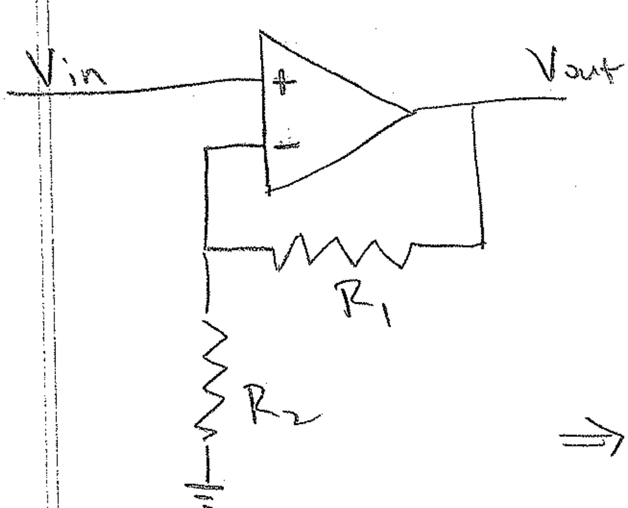
#1 and #2 imply that $I(R_1) + I(R_2) = 0$
and $V_- = 0$

so $V_{in}/R_1 + V_{out}/R_2 = 0$

$$\Rightarrow \boxed{V_{out} = -\frac{R_2}{R_1} V_{in}}$$

Since V^- is a "virtual ground" in this case,
input impedance $= R_1$.

"non-inverting amplifier"



rules imply

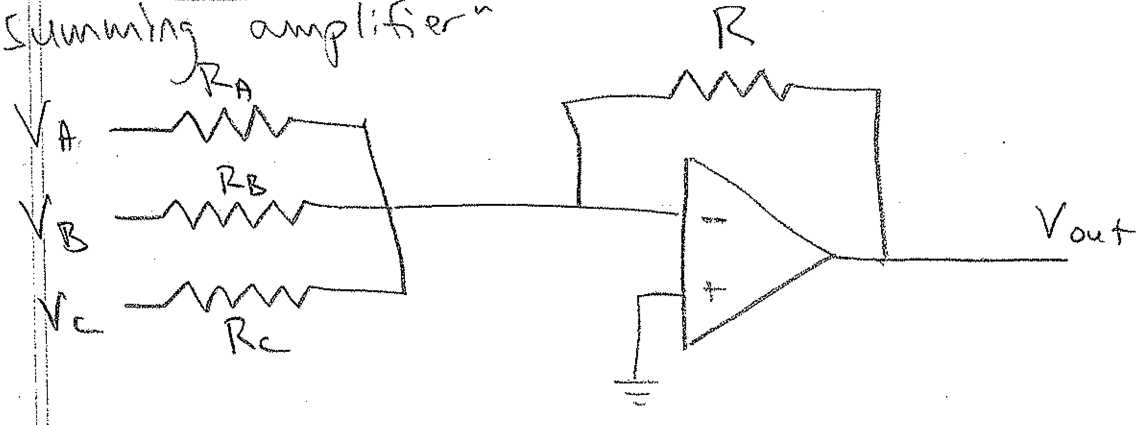
$$V_{out} \times \frac{R_2}{R_1 + R_2} = V_{in}$$

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

$$\boxed{V_{out} = V_{in} \left(1 + R_1/R_2\right)}$$

In this case, R_{IN} = "∞" (very high impedance)
idealization

"summing amplifier"



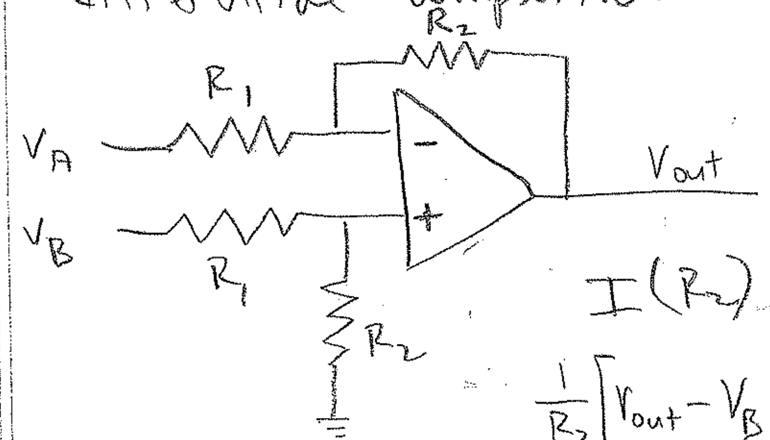
Because V_- is "virtual ground,"

$$-V_{OUT}/R = \frac{V_A}{R_A} + \frac{V_B}{R_B} + \frac{V_C}{R_C}$$

$$V_{OUT} = -\left[V_A \cdot \frac{R}{R_A} + V_B \cdot \frac{R}{R_B} + V_C \cdot \frac{R}{R_C}\right]$$

Can you think of a way to include a coefficient of opposite sign?

"differential amplifier"

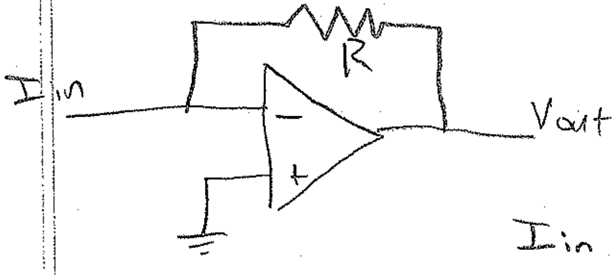


$$I(R_2) + I(R_1) = 0 \Rightarrow$$

$$\frac{1}{R_2}\left[V_{out} - V_B\frac{R_2}{R_1+R_2}\right] + \frac{1}{R_1}\left[V_A - V_B\frac{R_2}{R_1+R_2}\right] = 0$$

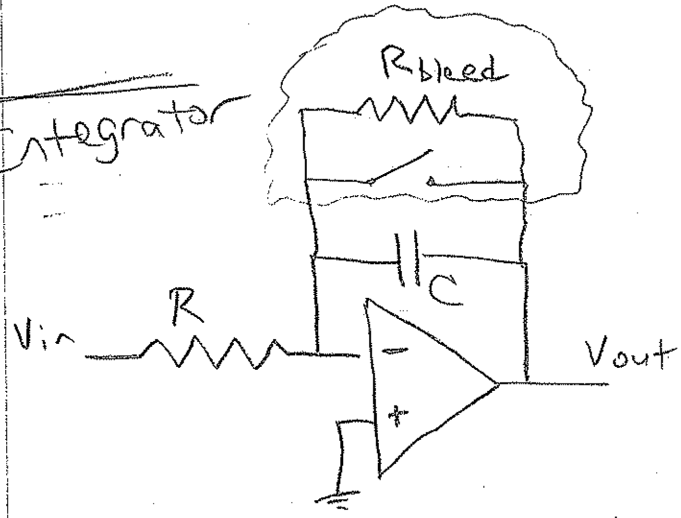
(after some algebra) $\Rightarrow V_{out} = \frac{R_2}{R_1}\left(V_B - V_A\right)$

Current-to-voltage amplifier



$$I_{in} + \frac{V_{out}}{R} = 0 \Rightarrow V_{out} = -R I_{in}$$

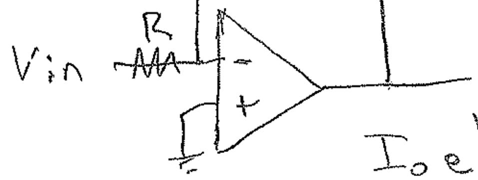
Integrator



Neglecting R_{bleed}, $C\frac{dV_{out}}{dt} + \frac{V_{in}}{R} = 0$

$$\Rightarrow V_{out} = -\frac{1}{RC}\int dt\, V_{in}(t)$$

This will saturate at $\pm V_{supply}$ rails unless capacitor is discharged with a reset switch or a bleeder resistor.



Using $I_{diode} \sim I_0 e^{V_{diode}/25\,mV}$ (see Shockley diode equation)

$$I_0 e^{V_{out}/25\,mV} + \frac{V_{in}}{R} = 0$$

$$V_{out} = -25\,mV \log\left(V_{in}/I_0 R\right)$$

logarithmic amplifier