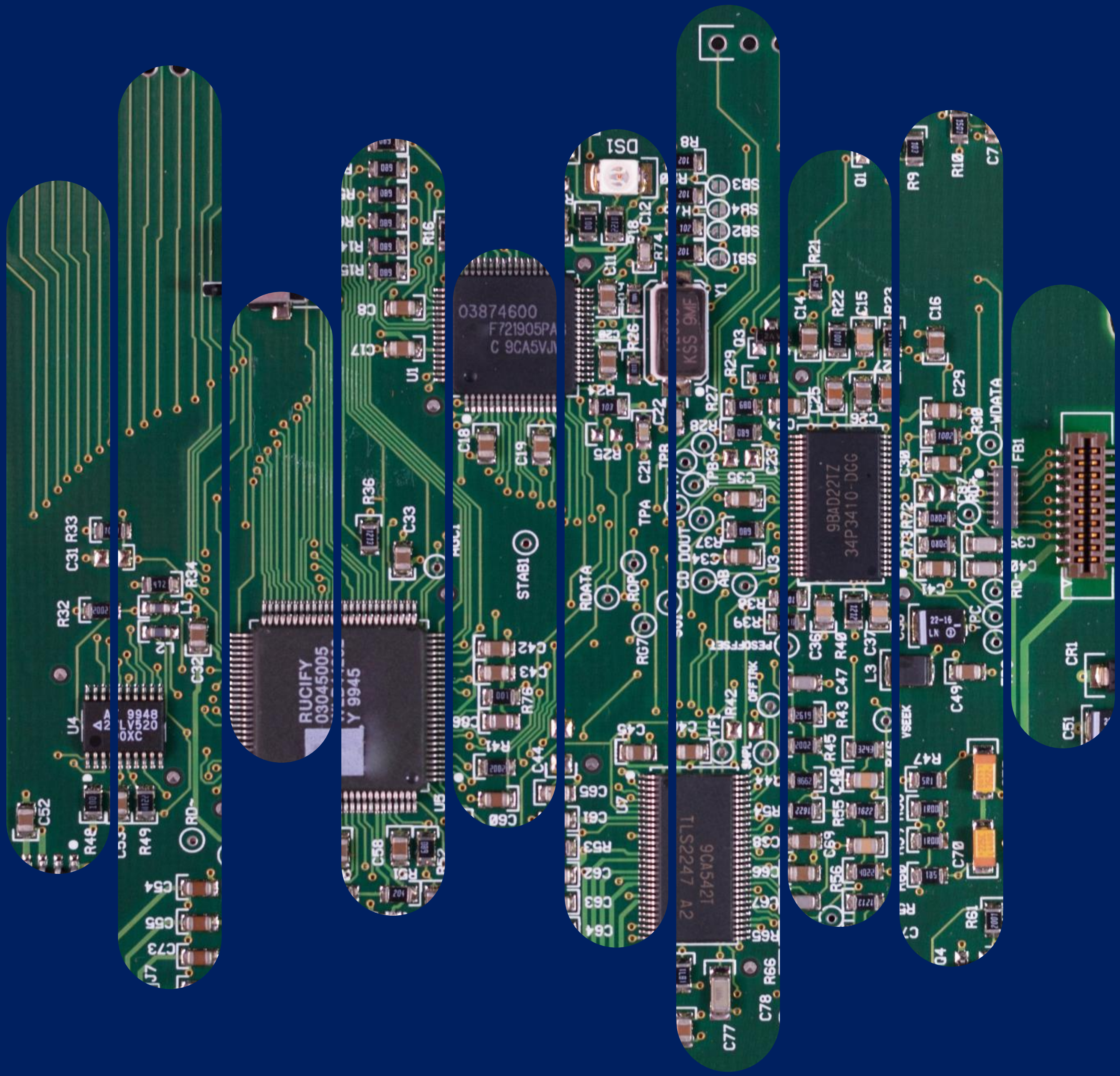
Electronic Devices

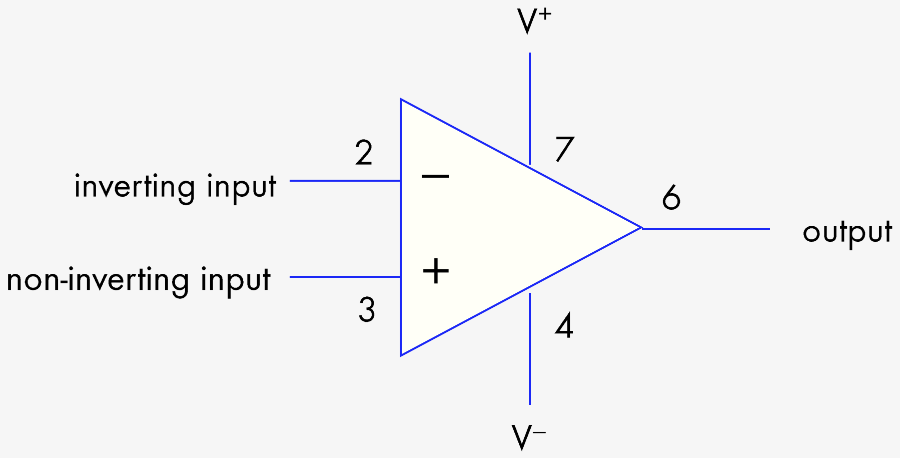


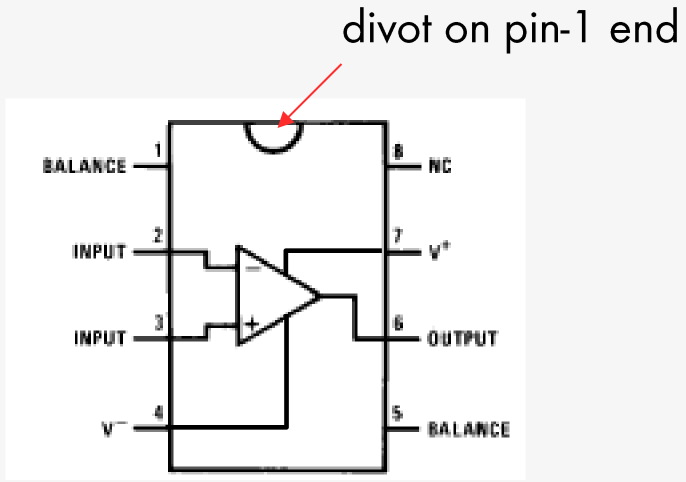
CHAPTER 9

Operational Amplifiers

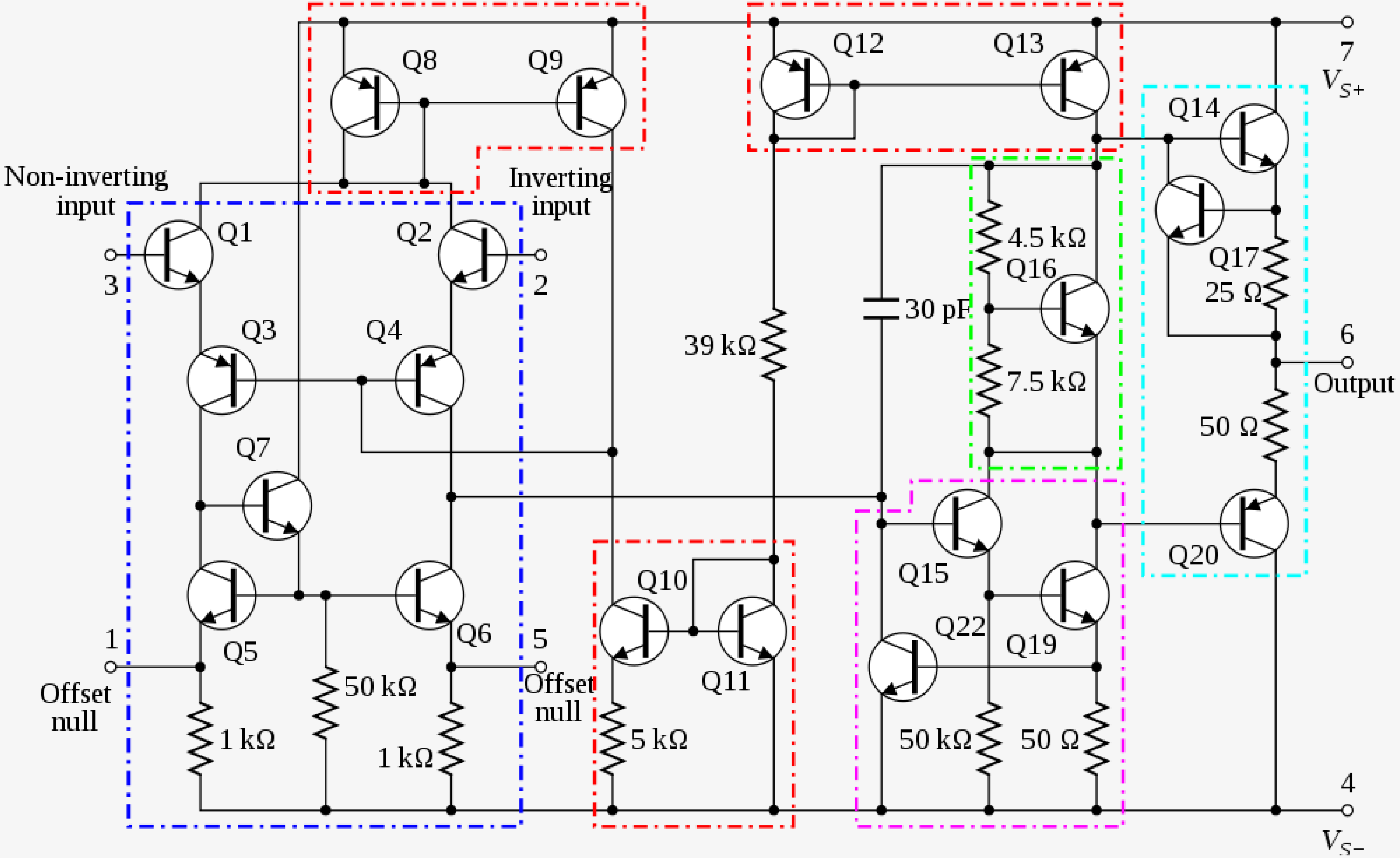
Op-Amp

- 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)





Internal Circuitry of Op-Amp



The ideal op-amp

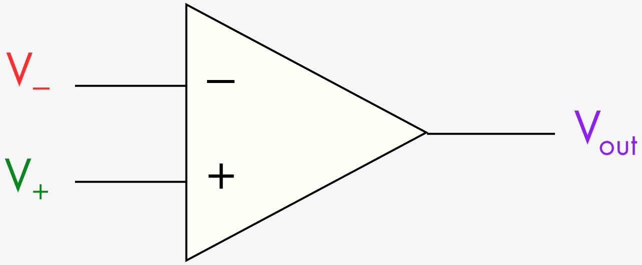
- Infinite voltage gain
  - a voltage difference at the two inputs is magnified infinitely
  - in truth, something like 200,000
  - means difference between + terminal and – terminal is amplified by 200,000!
- Infinite input impedance
  - no current flows into inputs
  - in truth, about $10^{12}\ \Omega$ 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 without feedback

- The internal op-amp formula is:

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

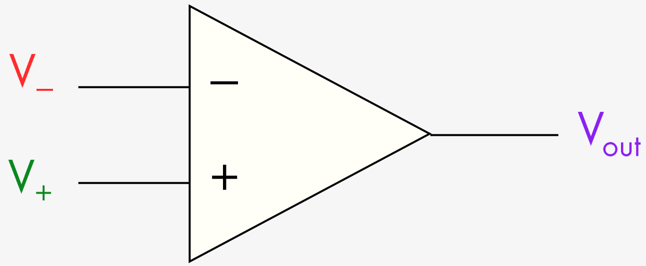
- So if V_+ is greater than V_-, the output goes positive
- If V_- is greater than V_+, the output goes negative



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

Virtual Ground and CMMR

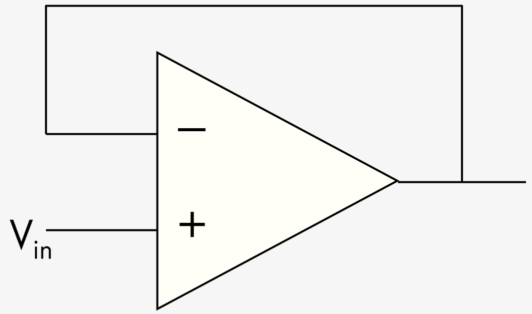
Virtual Ground means that the voltage at both input terminals of the op-amp is **almost equal**, even though no direct physical connection exists between them.



CMRR is a measure of how well an op-amp rejects **common-mode signals** (signals that appear equally on both input terminals)

Infinite gain in negative feedback

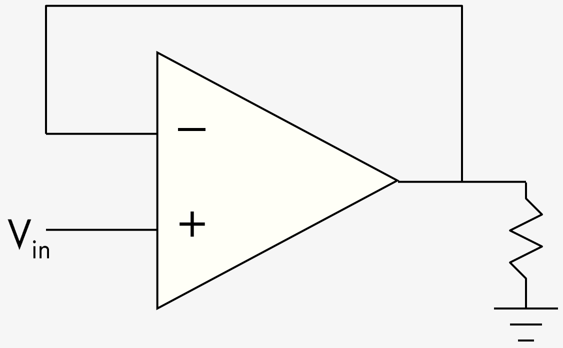
- Infinite gain would be useless except in the self-regulated negative feedback regime
  - negative feedback seems bad, and positive good—but in electronics positive feedback means runaway or oscillation, and negative feedback leads to stability
- Imagine hooking the output to the inverting terminal:
- 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

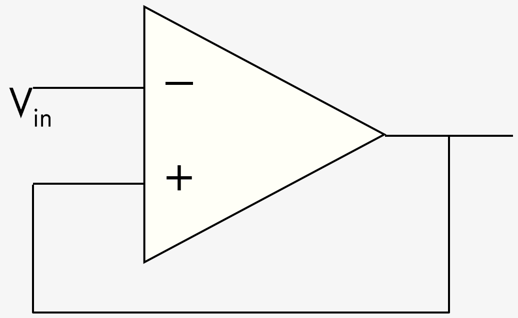
- Even if we load the output (which as pictured wants to drag the output to ground)...
  - the op-amp will do everything it can within its current limitations to drive the output until the inverting input reaches V_{in}
  - negative feedback makes it self-correcting
  - in this case, the op-amp drives (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

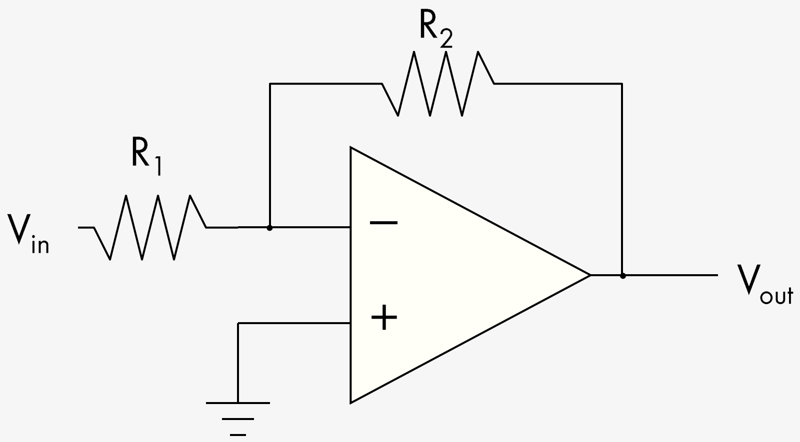
- In the configuration below, if the + input is even a smidge higher than V_{in}, the output goes way positive
- This makes the + terminal even *more* positive than V_{in}, making the situation worse
- This system will immediately “rail” at the supply voltage
  - could rail either direction, depending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



Op-Amp "Golden Rules"

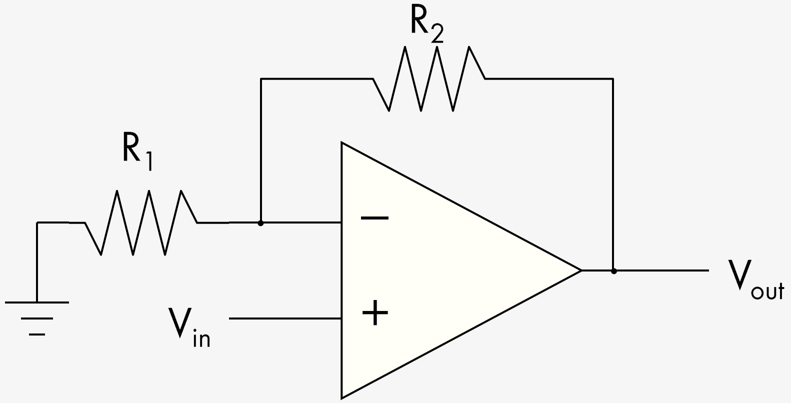
- When an op-amp is configured in *any* negative-feedback arrangement, it will obey the following two rules:
  - The inputs to the op-amp draw or source no current (true whether negative feedback or not)
  - The op-amp output will do whatever it can (within its limitations) to make the voltage difference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

Inverting amplifier



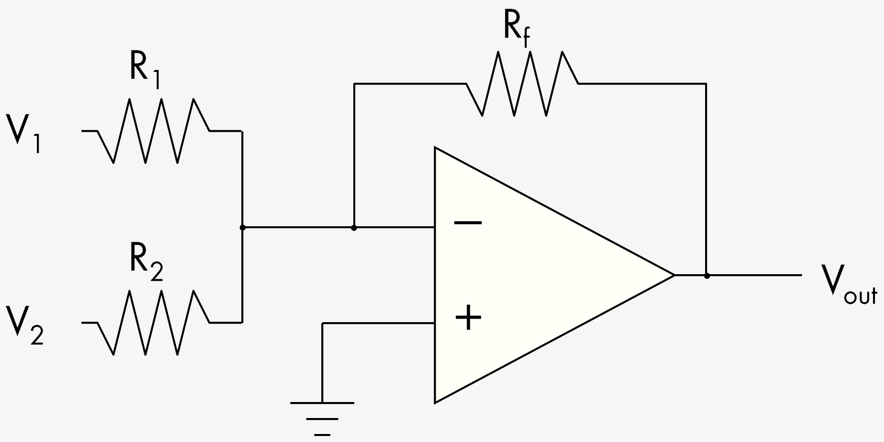
- Applying the rules: – terminal at "virtual ground"
  - so current through R_1 is $I_f = V_{in}/R_1$
- Current does not flow into op-amp (one of our rules)
  - so the current through R_1 must go through R_2
  - voltage drop across R_2 is then $I_f R_2 = V_{in} \times (R_2/R_1)$
- So $V_{out} = 0 - V_{in} \times (R_2/R_1) = -V_{in} \times (R_2/R_1)$
- 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



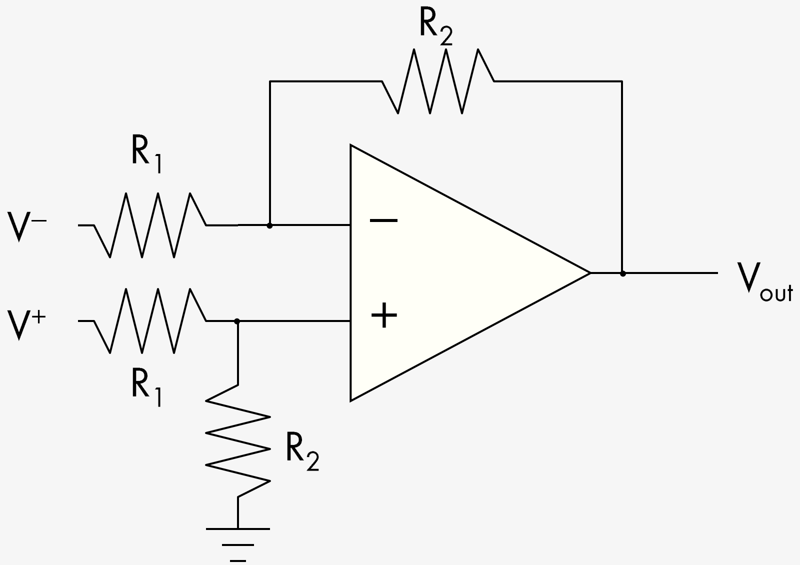
- Now neg. terminal held at V_{in}
  - so current through R_1 is $I_f = V_{in}/R_1$ (to left, into ground)
- This current cannot come from op-amp input
  - so comes through R_2 (delivered from op-amp output)
  - voltage drop across R_2 is $I_f R_2 = V_{in} \times (R_2/R_1)$
  - so that output is higher 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

Summing amplifier



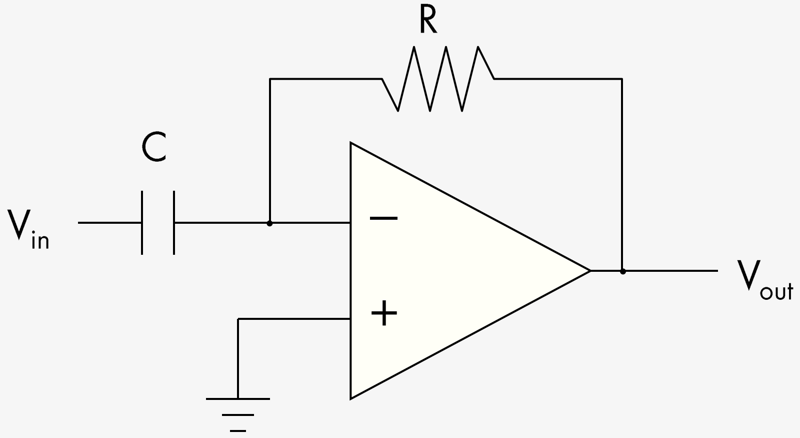
- Much like the inverting amplifier, but with two input voltages
  - inverting input still held at virtual ground
  - I_1 and I_2 are added together to run through R_f
  - so we get the (inverted) sum: $V_{out} = -R_f \times (V_1/R_1 + V_2/R_2)$
    - if $R_2 = R_1 = R_f$ we get a sum proportional to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

Differencing amplifier



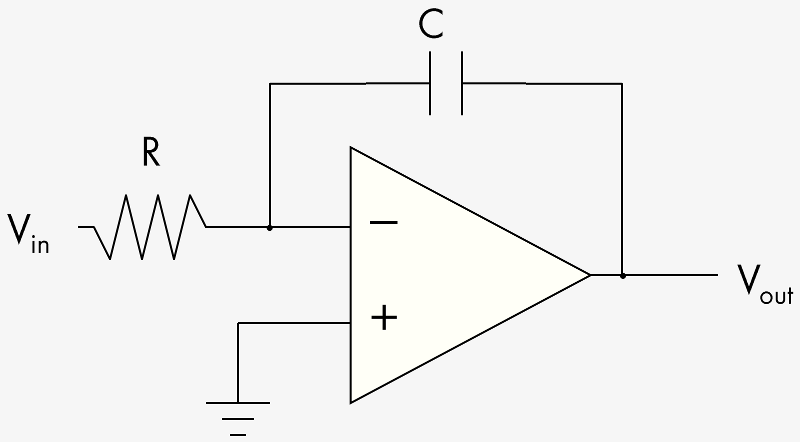
- The non-inverting input is a simple voltage divider:
  - $V_{node} = V^{+}R_2/(R_1 + R_2)$
- So $I_f = (V^{-} - V_{node})/R_1$
  - $V_{out} = V_{node} - I_f R_2 = V^{+}(1 + R_2/R_1)(R_2/(R_1 + R_2)) - V^{-}(R_2/R_1)$
  - so $V_{out} = (R_2/R_1)(V^{+} - V^{-})$
  - therefore we difference V^{+} and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

Differentiator (high-pass)



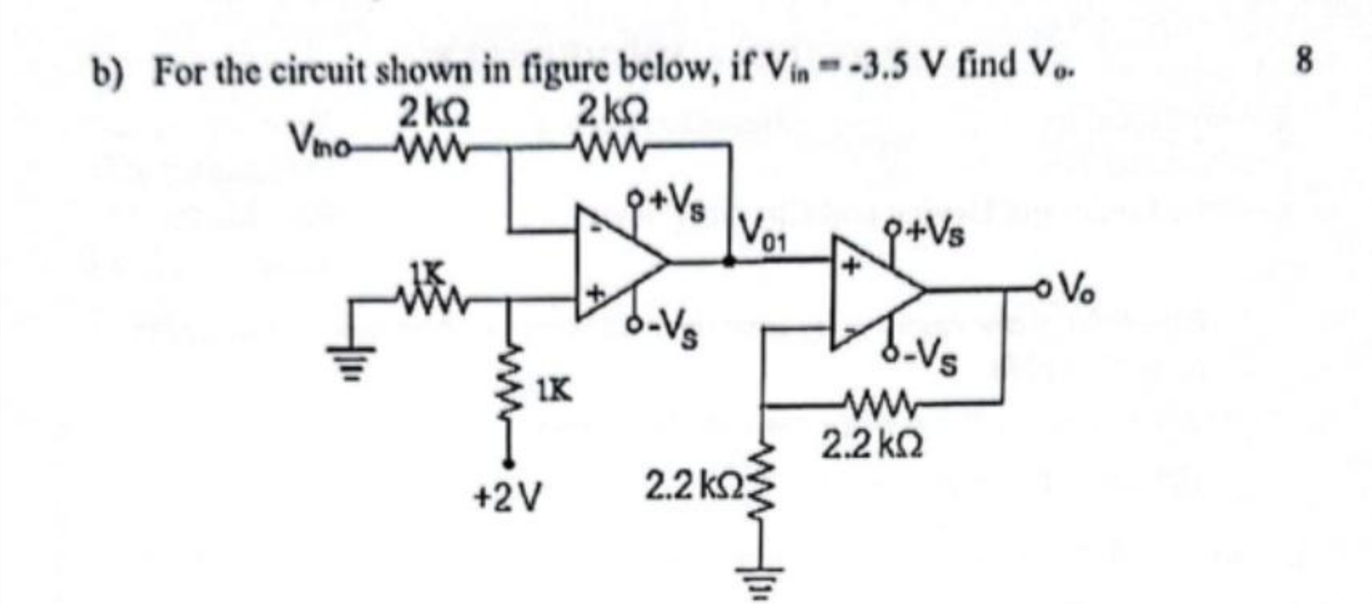
- For a capacitor, $Q = CV$, so $I_{cap} = dQ/dt = C{\cdot}dV/dt$
  - Thus $V_{out} = -I_{cap}R = -RC{\cdot}dV/dt$
- So we have a differentiator, or high-pass filter
  - if signal is $V_0 \sin\omega t$, $V_{out} = -V_0 RC\omega \cos\omega t$
  - the ω-dependence means higher frequencies amplified more

Low-pass filter (integrator)



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

    $-dV_{out}/dt = V_{in}/RC$
  - so $$V_{\text{out}} = -\frac{1}{RC}\int V_{in}dt$$
  - and therefore we have an integrator (low pass)



Given,

$V_{in} = -3.5V$

Now at first op-amp,

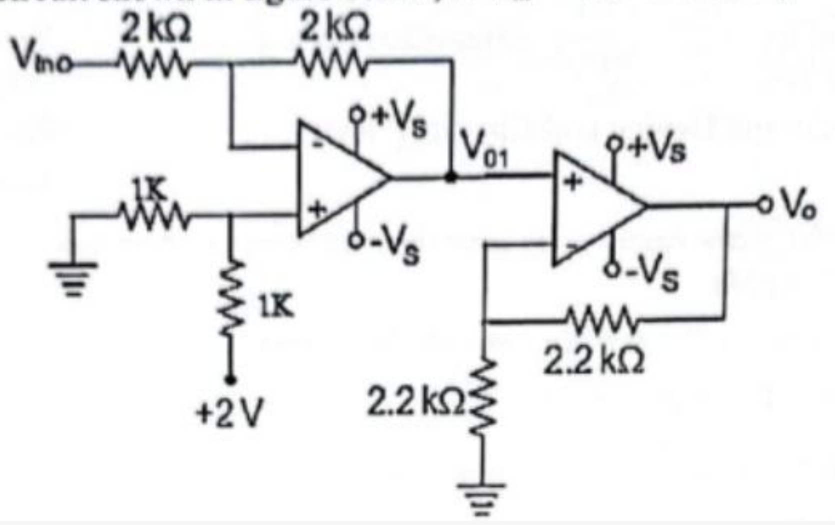
$$V^+ = 2 \times \frac{1}{1+1} = 1V$$

As, we know voltage at inverting terminal is equal to non-inverting terminal

$V^- = 1V$

We know that input current is zero in op-amps. Therefore,

b) For the circuit shown in figure below, if $V_{in} = -3.5$ V find V_o. 8



$$\frac{V_{in} - V^-}{2} = \frac{V^- - V_{o1}}{2}$$

$$V_{o1} = V^- - V_{in} + V^- = 1 + 3.5 + 1 = 5.5V$$

Now at second op-amp,

$$\frac{0 - V_{o1}}{2.2} = \frac{V_{o1} - V_o}{2.2}$$

$$V_o = V_{o1} + V_{o1} = 5.5 + 5.5 = 11V$$

Design a summing operational amplifier circuit that will produce an output voltage $V_{out} = -4V_1 - V_2 + 0.1V_3$

Given,

$$V_{out} = -4V_1 - V_2 + 0.1V_3$$

$$V_{out} = -4V_1 - V_2 - 0.1(-V_3)$$

Standard form of summing op-amp circuit is,

$$V_{out} = -\frac{R_f}{R_1}V_1 - \frac{R_f}{R_2}V_2 - \frac{R_f}{R_3}V_3$$

First, we need to invert V_3

Let's take, $R_f = 10K\Omega$

For gain = -1, R_f is equal to the input resistance, therefore, 10K

Design a summing operational amplifier circuit that will produce an output voltage $V_{out} = -4V_1 - V_2 + 0.1V_3$

Now,

$$R_1 = \frac{R_f}{4} = \frac{10}{4} = 2.5K\Omega$$

$$R_2 = \frac{R_f}{1} = \frac{10}{1} = 10K\Omega$$

$$R_3 = \frac{R_f}{0.1} = \frac{10}{0.1} = 100K\Omega$$