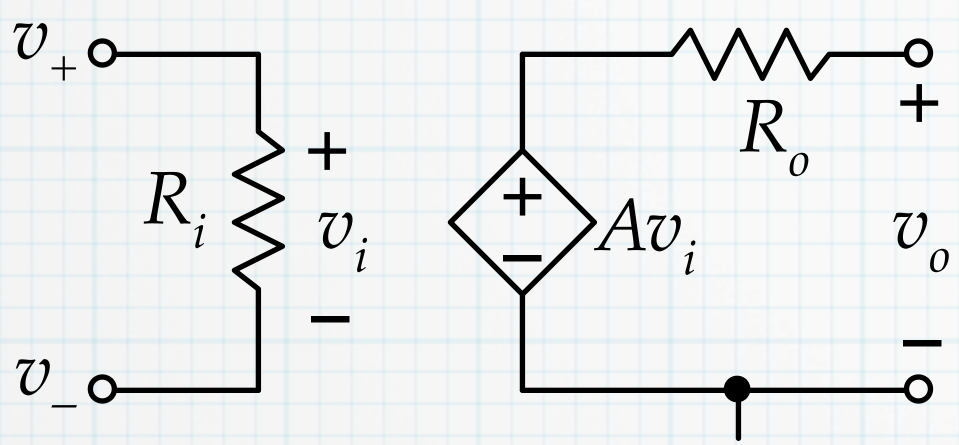
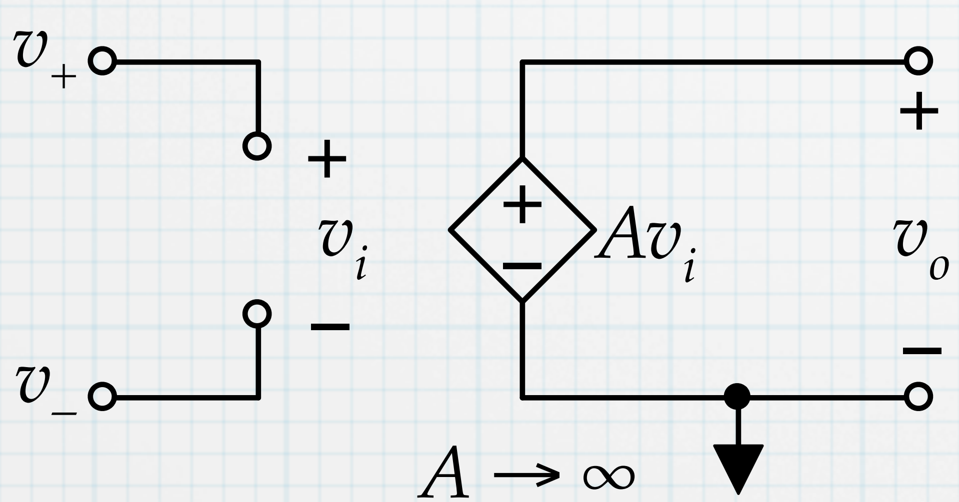
Operational amplifiers (Op amps)



View it as an ideal amp.

Take the properties to the extreme: $R_i \to \infty$, $R_o = 0$, $A \to \infty$. ?!?!?!?!



Consequences: No voltage dividers at input or output. (That's good.)
No current flows into the input. (That's good.)
The gain is infinite. (Is that good?)

How do we handle this infinite gain business?

$$v_o = A v_i$$

In order to keep v_o finite, then as $A \to \infty$, $v_i \to 0$. In other words, we must force the difference signal at the input to go to zero. How do we do that? With feedback, of course.

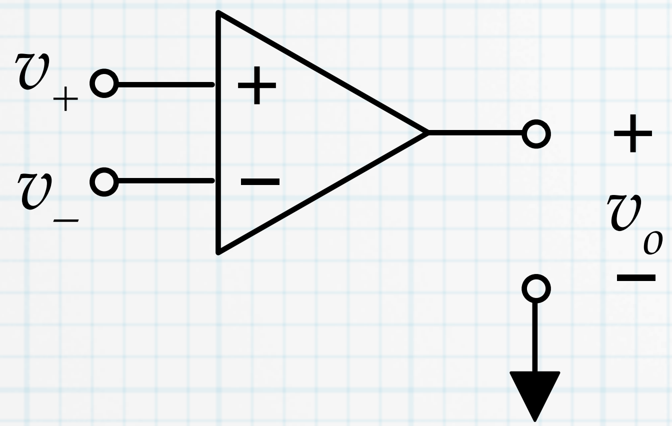
Recall that the difference signal in a feedback arrangement must become very small if the gain is very big.

$$S_d = \frac{1}{1 + A\beta} S_i \ \to 0, \text{ as } A \to \infty$$

One input is connected to the source voltage in some fashion. The other input is connected to the feedback network. If the feedback is working properly, then $v_i = v_+ - v_- = 0$.

The condition of $v_+ = v_-$ is called a *virtual short* at the input. This should be the case, if negative feedback is working in the circuit.

Ideal op amp



$v_+ \rightarrow$ non-inverting input

$v_- \rightarrow$ inverting input

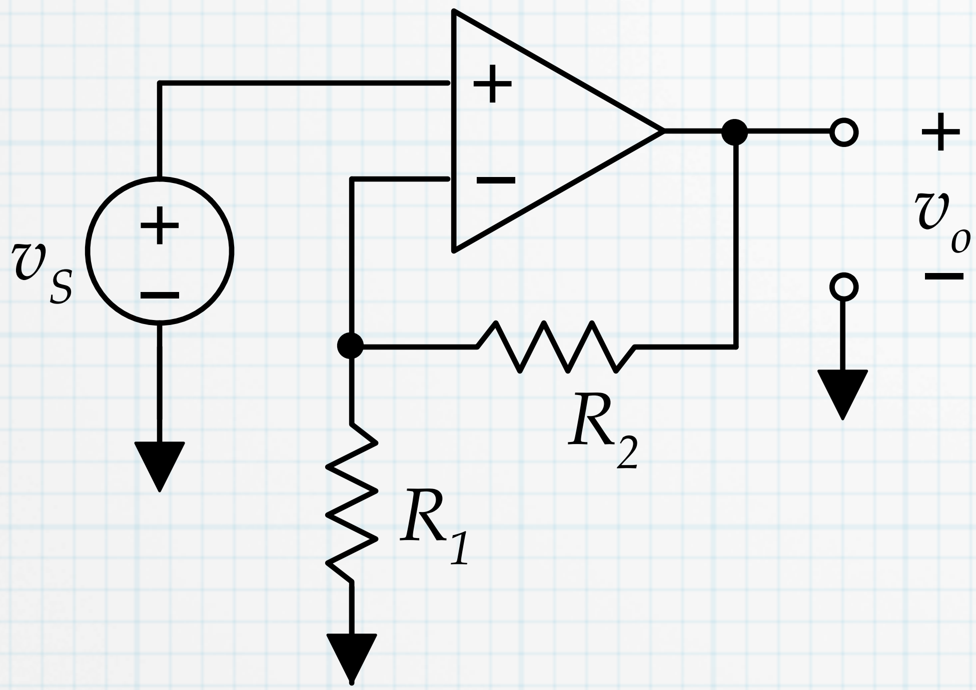
When using an op amp in a circuit:

$v_+ \approx v_- \rightarrow$ virtual short (assuming a proper negative feedback configuration.)

$i_+ = i_- = 0 \rightarrow$ due to infinite input resistance

No voltage divider effects at output. This means that we can connect anything to the output without worrying about loading effects.

Non-inverting amplifier



Write a node equation at the inverting terminal.

$$\frac{v_o - v_-}{R_2} = \frac{v_-}{R_1} + i_-$$

$v_- = v_+ = v_s$ (virtual short due to feedback)

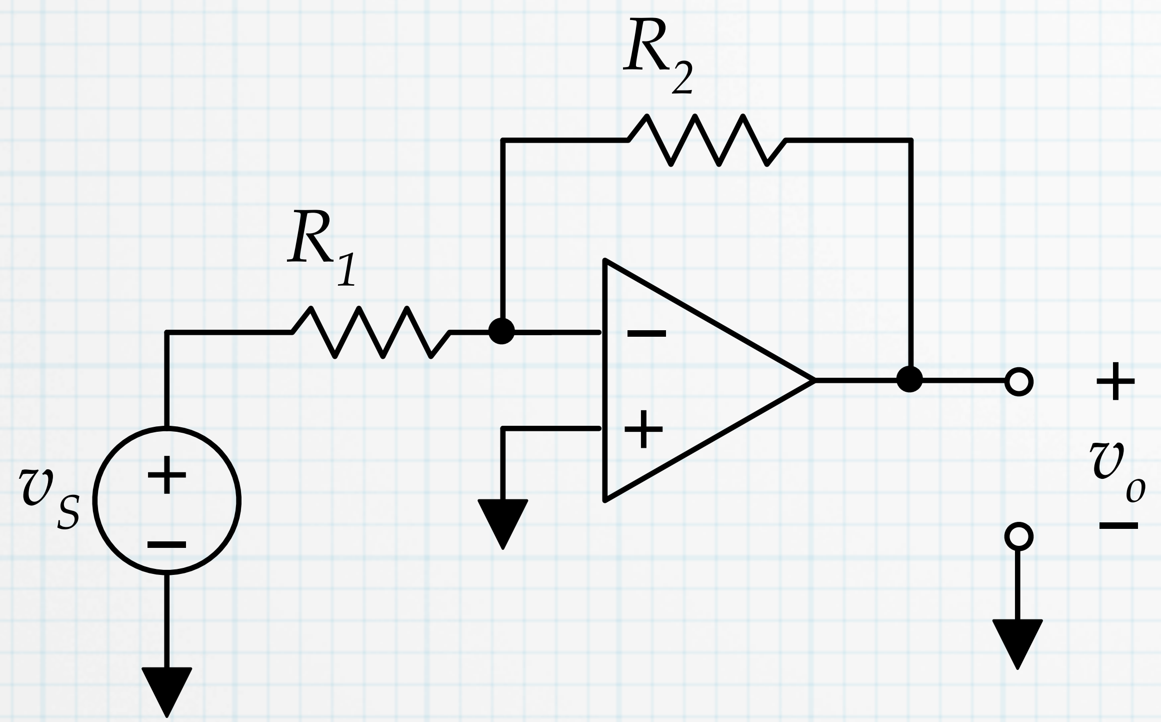
$i_- = 0$ (infinite input resistance)

$$\frac{v_o - v_S}{R_2} = \frac{v_S}{R_1}$$

$$G = \frac{v_o}{v_S} = \frac{R_1 + R_2}{R_1} = 1 + \frac{R_2}{R_1}$$

(Worth memorizing.)

Inverting amplifier



Write a node equation at the inverting terminal.

$$\frac{v_s - v_-}{R_1} = \frac{v_- - v_o}{R_2} + i_-$$

$v_- = v_+ = 0$ (virtual ground!)
$i_- = 0$ (infinite input resistance)

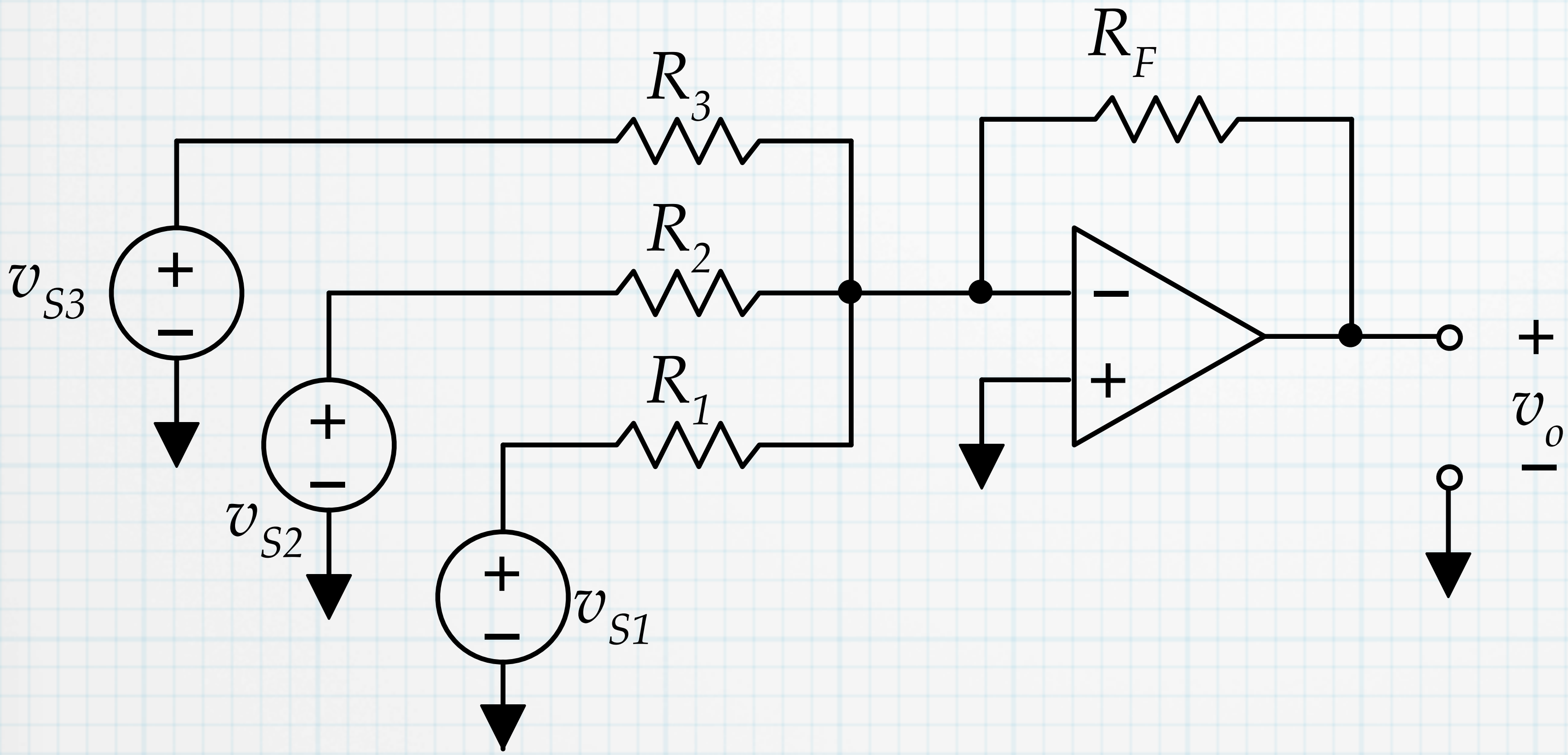
$$\frac{v_s}{R_1} = \frac{-v_o}{R_2}$$

$$G = \frac{v_o}{v_S} = -\frac{R_2}{R_1}$$

Note the negative sign!

(Also worth memorizing.)

Summing amp (weighted summer)



At the inverting terminal: $v_- = v_+ = 0$ (virtual ground). Write a node equation there. (Or use superposition.)

$$\frac{v_{S1}}{R_1} + \frac{v_{S2}}{R_2} + \frac{v_{S3}}{R_3} = \frac{-v_o}{R_F}$$

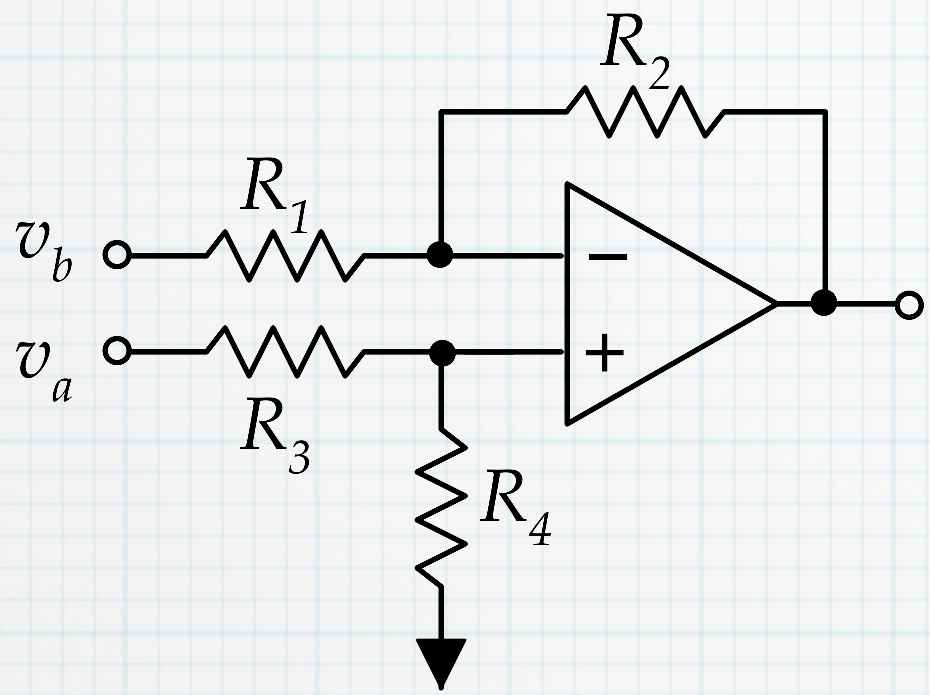
$$v_o = -\left(\frac{R_F}{R_1}v_{S1} + \frac{R_F}{R_2}v_{S2} + \frac{R_F}{R_3}v_{S3}\right)$$

Use another inverter if you don't like the negative sign.

The "virtually grounded" inverting terminal becomes a summing node.

Difference amp

We would like to amplify only the difference between v_a and v_b. Anything this applied in common to both, will not be amplified.



At the inverting input:

$$\frac{v_b - v_-}{R_1} = \frac{v_- - v_o}{R_2}$$

$$v_o = \left(1 + \frac{R_2}{R_1}\right) v_- - \frac{R_2}{R_1} v_b$$

At the non-inverting input:

$$\frac{v_a - v_+}{R_3} = \frac{v_+}{R_4}$$

$$v_+ = \frac{R_4}{R_3 + R_4} v_a$$

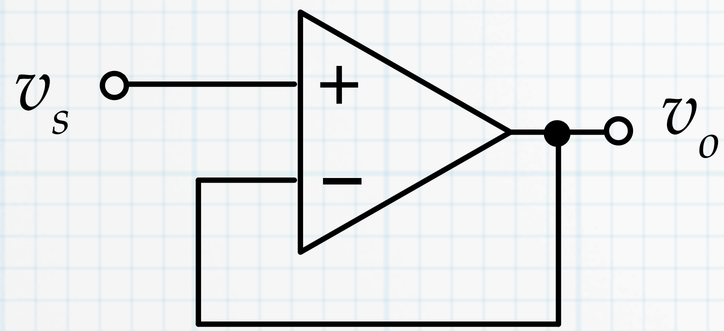
$$v_+ = v_-$$

$$v_o = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_4}{R_3 + R_4} v_a\right) - \frac{R_2}{R_1} v_b$$

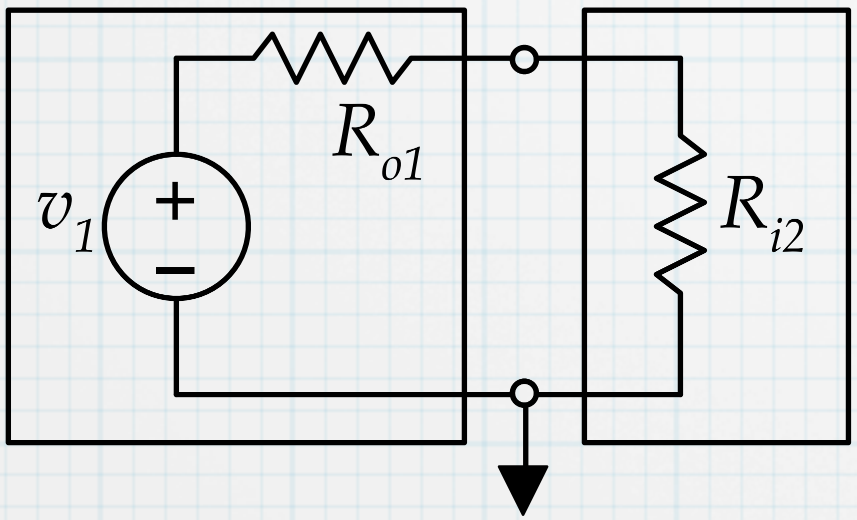
if $\frac{R_2}{R_1} = \frac{R_4}{R_3}$ then $v_o = \frac{R_2}{R_1}(v_a - v_b)$

Difference only!
(Check it.)

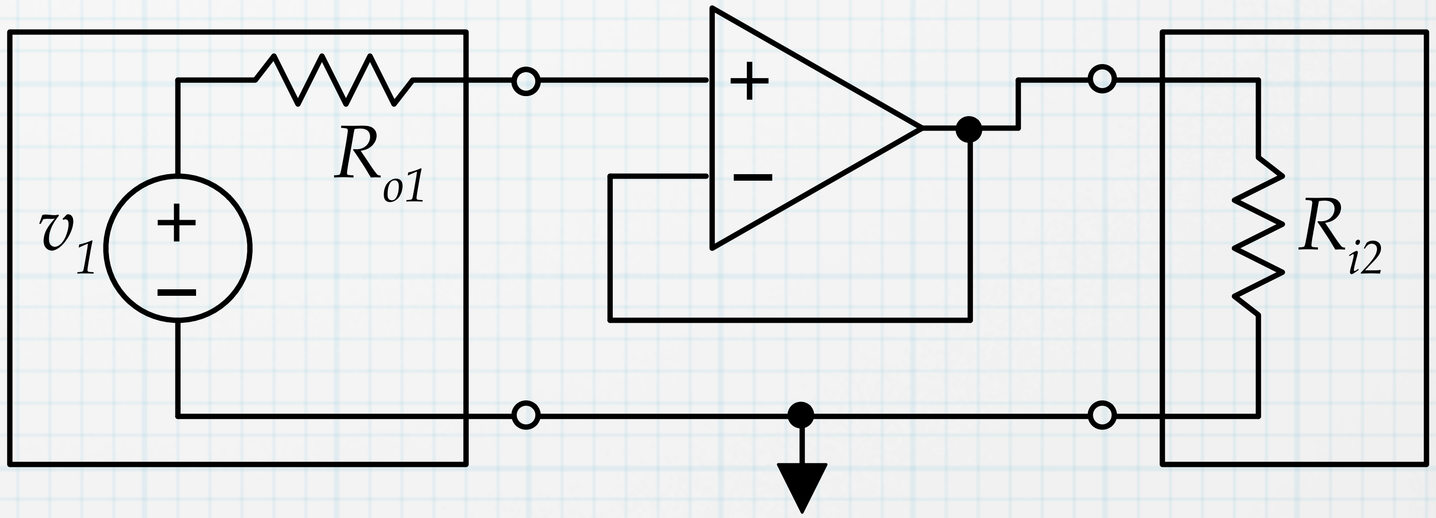
Unity gain buffer



Non-inverting amp with $R_2 = 0$ and $R_1 \rightarrow \infty$. So G = 1, meaning $v_o = v_s$. What good is that?



Connecting two circuits. If $R_{o1} > R_{i2}$, then much of the voltage is lost in the voltage divider, $v_{i2} << v_1$.



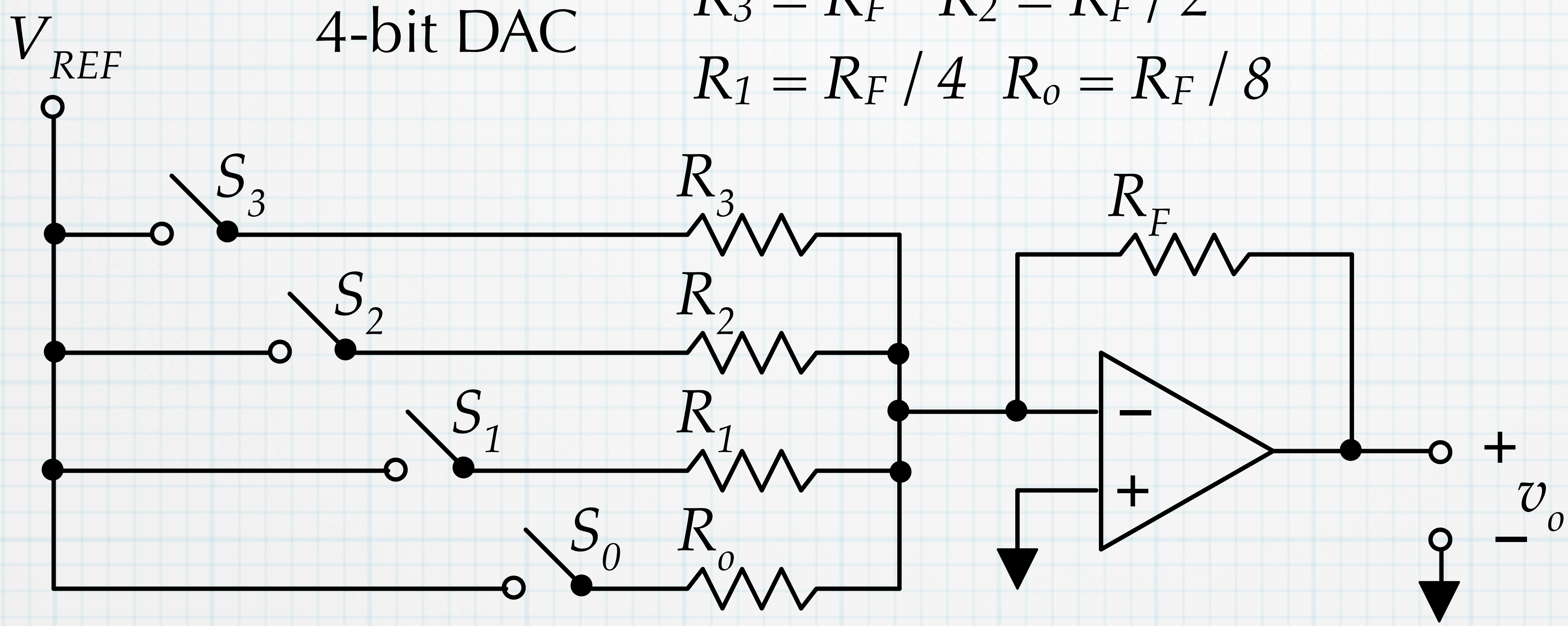
High input resistance of op amp makes $v_+ = v_1$. Zero output resistance of op amp makes $v_{i2} = v_o$. Since $v_o = v_+$, then $v_{i2} = v_1$. The op amp served as a buffer between the two circuits, eliminated the voltage divider problem.

Digital-to-analog converter (DAC)

Data is stored as digital information on your phone or computer. Some of that data needs to be converted to analog form in order to use it, i.e. music.

$R_3 = R_F \quad R_2 = R_F / 2$

$R_1 = R_F / 4 \quad R_o = R_F / 8$



$V_{REF} = \text{-1 V}$

S	v_o (V)
0000	0
0001	0.125
0010	0.25
0011	0.375
0100	0.5
0101	0.625
0110	0.75
0111	0.875
1000	1
1001	1.125
1010	1.25
1011	1.375
1100	1.5
1101	1.625
1110	1.75
1111	2

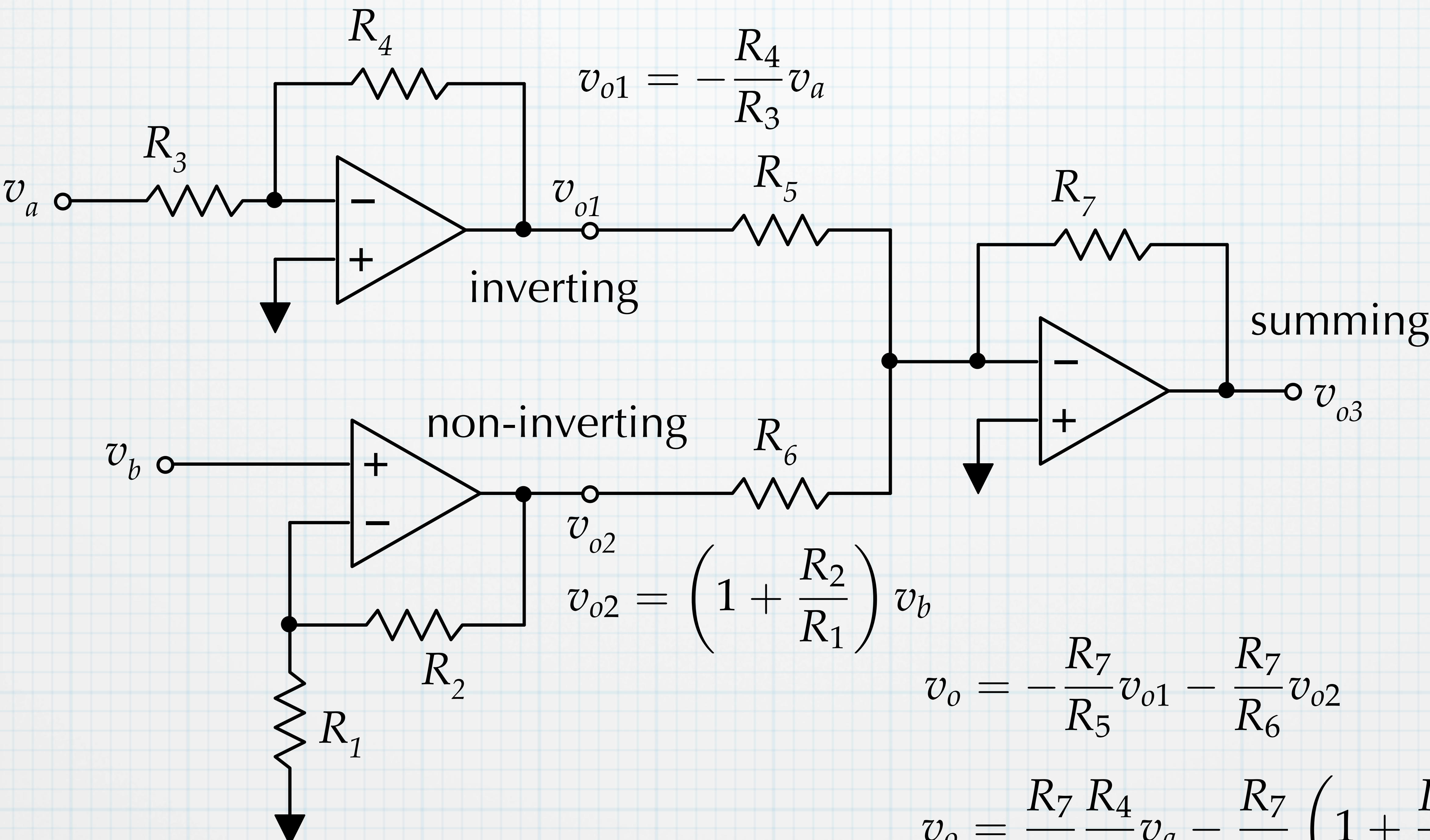
The digital bits control the operation of the switches – one bit per switch. $S_i = 0$, switch is open, $S_i = 1$ switch is closed.

S_o only closed: $v_o = -V_{REF}/8$. S_1 only closed: $v_o = -V_{REF}/4$.

S_2 only closed: $v_o = -V_{REF}/2$. S_3 only closed: $v_o = -V_{REF}$.

Cascading amps

The various types of circuits can serve as building blocks for more complicated circuits.

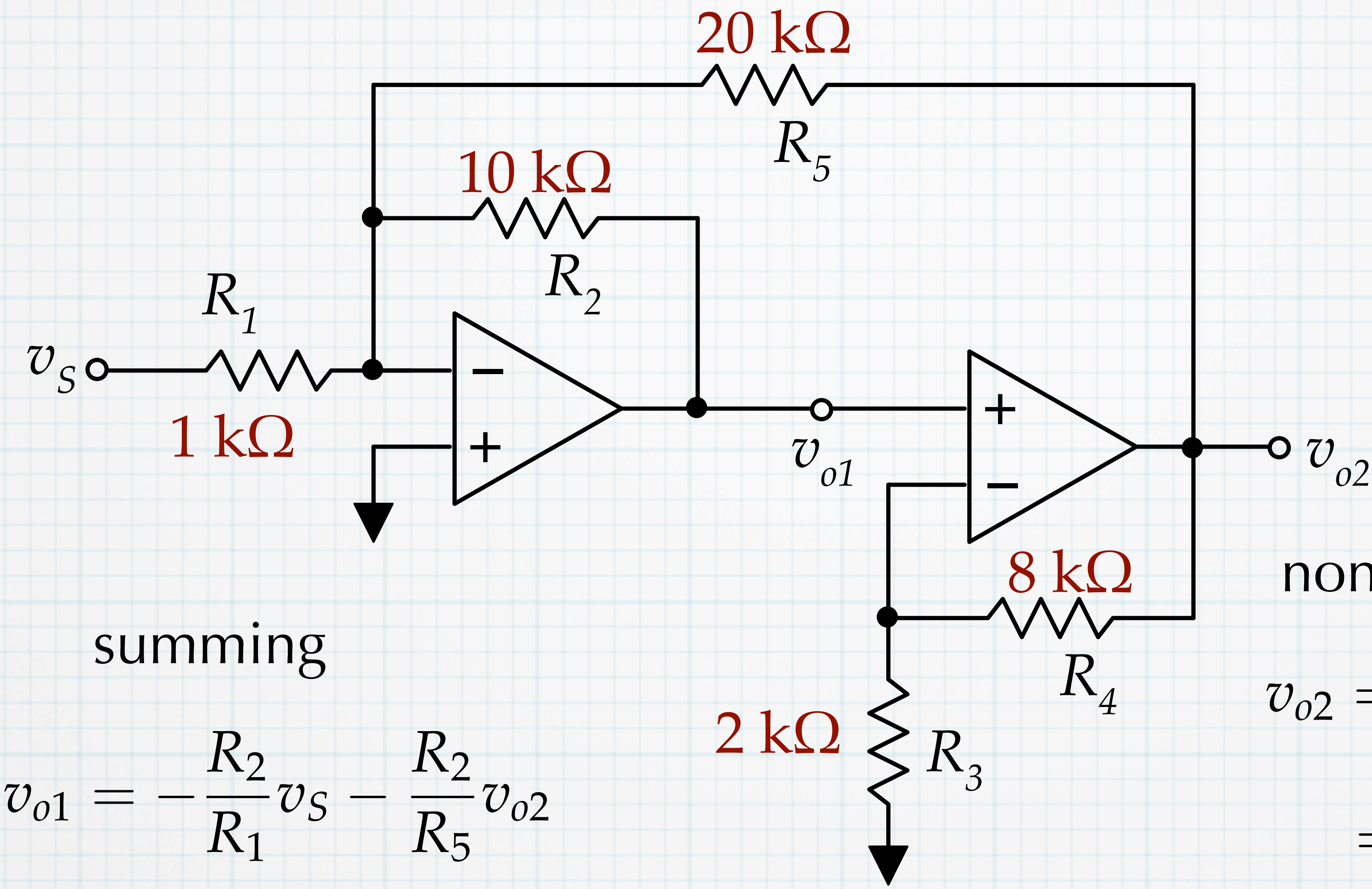


$$v_{o1} = -\frac{R_4}{R_3} v_a$$

$$v_{o2} = \left(1 + \frac{R_2}{R_1}\right) v_b$$

$$v_o = -\frac{R_7}{R_5} v_{o1} - \frac{R_7}{R_6} v_{o2}$$

$$v_o = \frac{R_7}{R_5}\frac{R_4}{R_3} v_a - \frac{R_7}{R_6}\left(1 + \frac{R_2}{R_1}\right) v_b$$



summing

$$v_{o1} = -\frac{R_2}{R_1} v_S - \frac{R_2}{R_5} v_{o2}$$

$$= -10 v_S - 0.5 v_{o2}$$

non-inverting

$$v_{o2} = \left(1 + \frac{R_4}{R_3}\right) v_{o1}$$

$$= 5 v_{o1}$$

want v_{o2} / v_S.

$$\frac{v_{o2}}{5} = -10 v_S - 0.5 v_{o2}$$

$$0.7 v_{o2} = -10 v_S$$

$$\frac{v_{o2}}{v_S} = -14.29$$

Feedback loop around feedback loops !!