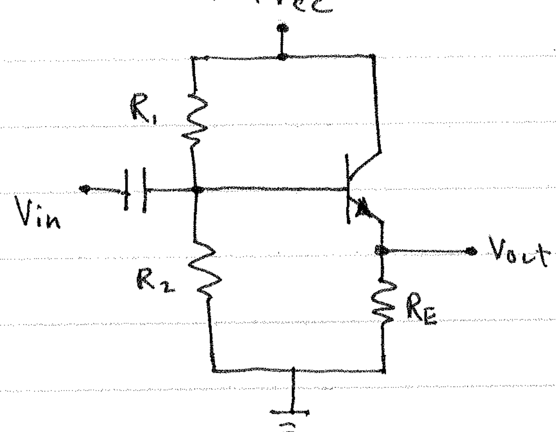
Notes on Operational Amplifiers:

- The common-emitter amplifier you have been studying (and building) ~~and~~ uses a single npn bipolar junction transistor.

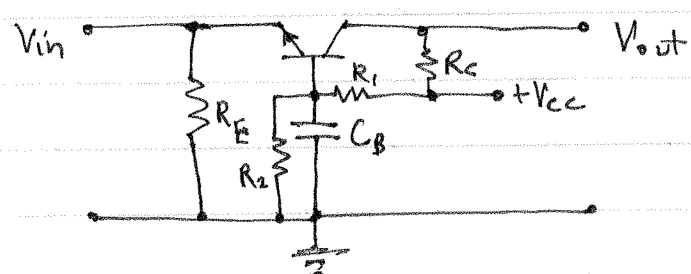
- Given more time, we might explore other circuits using a single BJT transistor.

For example ... the common-collector amplifier (or emitter follower)



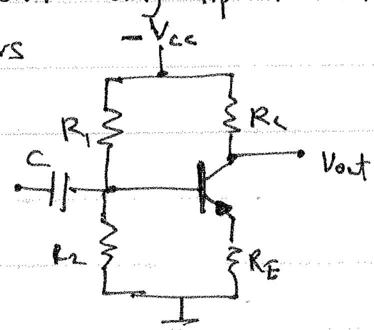
This amplifier has (approx.) unity voltage gain, but has high current gain ... low output resistance.

or the common-base amplifier



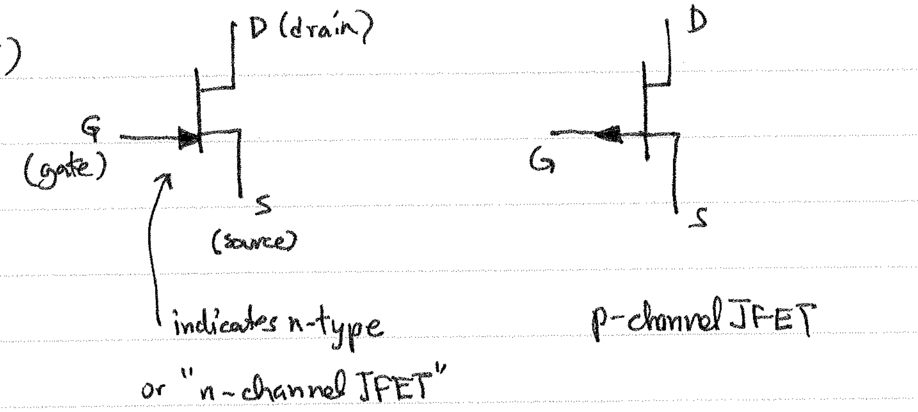
This amplifier has good voltage gain but small input impedance (small or no current gain). This circuit also works well at high frequencies.

We might also compare circuits using npn transistors to equivalent circuits with pnp transistors

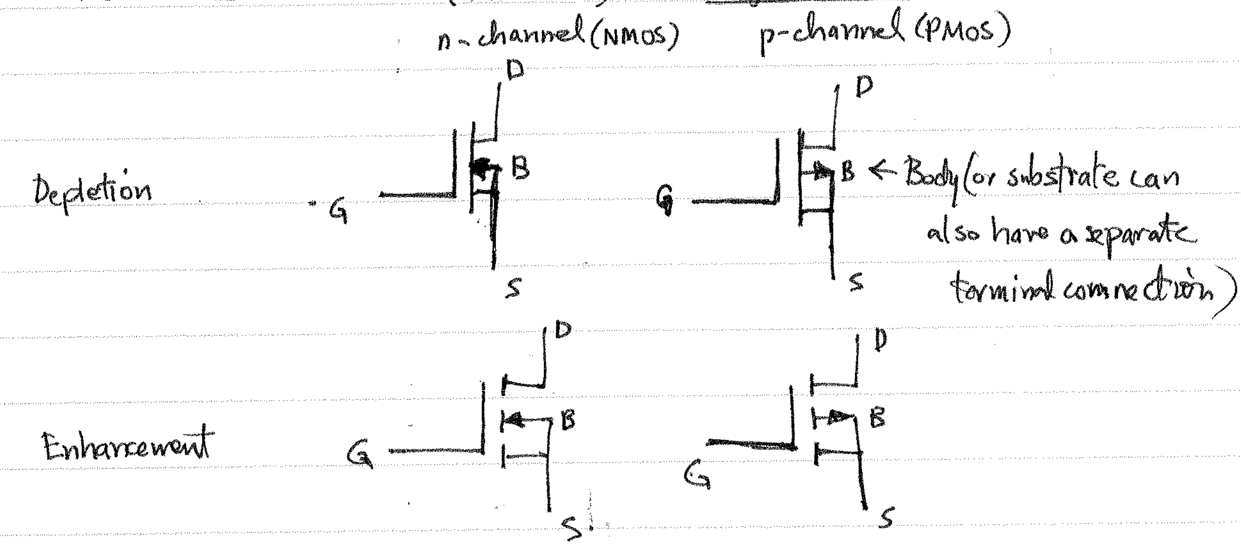


We might also look at circuits that use <u>Field Effect Transistors</u> (FETs).

- Junction FET (JFET)



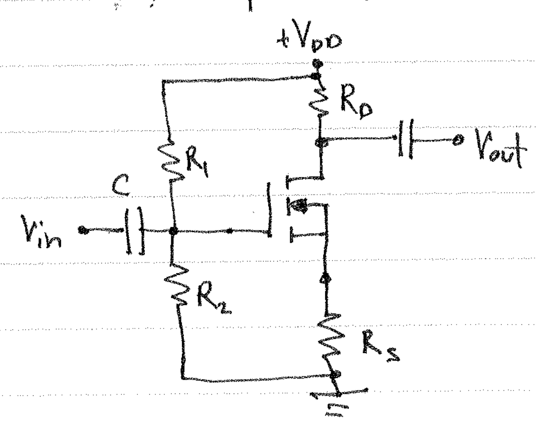
- Metal Oxide Semiconductor FET (MOSFET) – <u>integrated circuits</u>



No conduction between <u>gate</u> and the other two terminals. Gate voltage controls current flow from <u>drain</u> to <u>source</u>

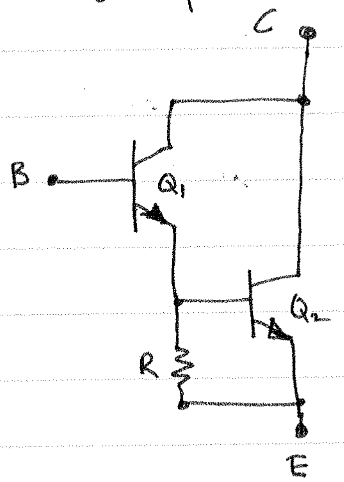
Many BJT circuits have FET versions

Example: Common-source Amplifier (w/ NMOS-enhancement)

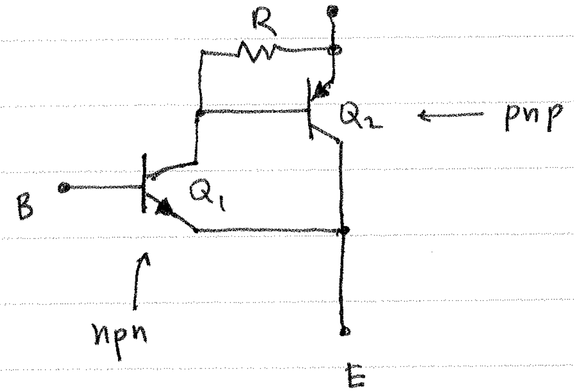


We might also look at circuits (or circuit elements) that use multiple transistors, like ...

- Darlington pair

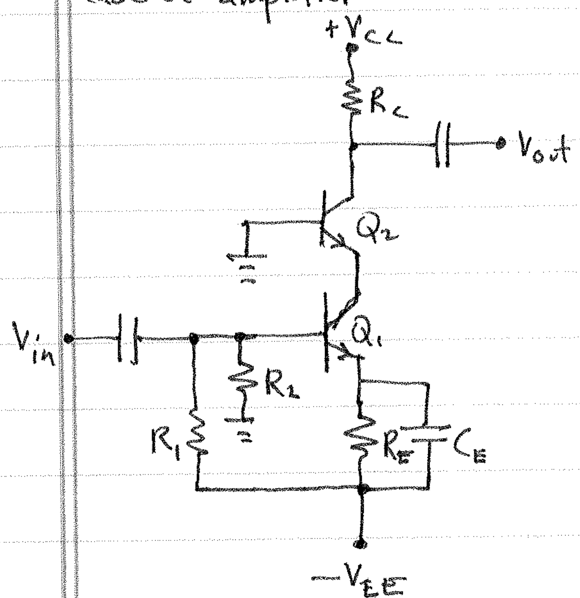


- Sziklai pair (or complementary Darlington)



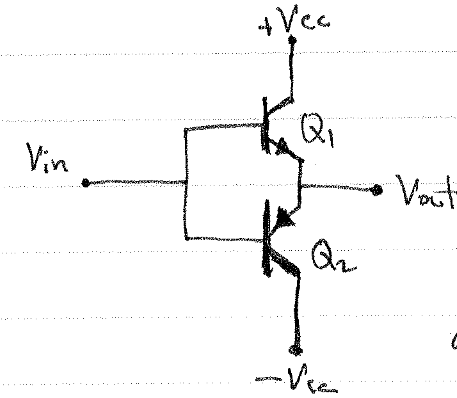
The two-transistor combinations act like a single transistor with a much higher current gain (β).

- Cascode amplifier



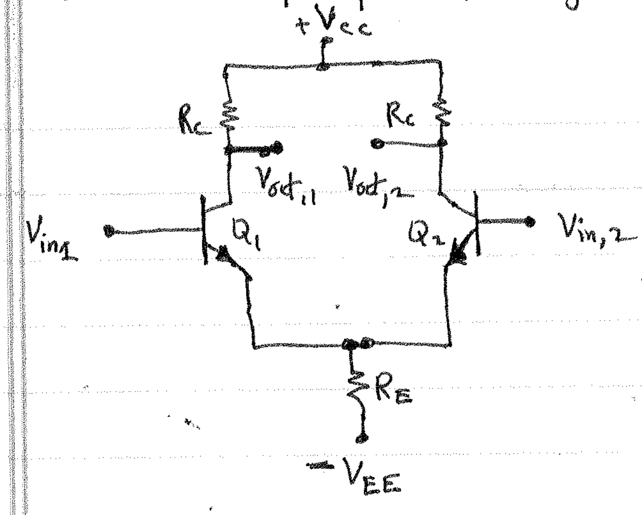
This is essentially a common-emitter amplifier followed by a common-base amplifier. It has better high frequency performance than the standard common-emitter (single-stage) amplifier

- Push-pull configuration (emitter follower)



only one transistor is "on" at a time reducing the quiescent power dissipation in output stages of amplifiers.

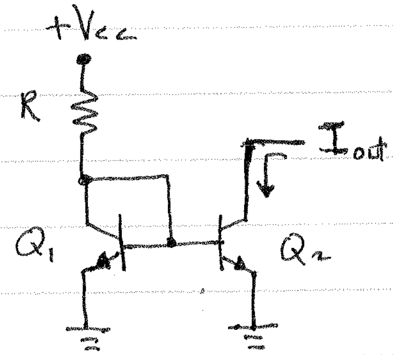
- An emitter-coupled pair (or "long-tailed pair") or differential amplifier



This circuit amplifies the difference between the input signals and "ignores" the "common-mode" part of input signals. It is the basic input stage for an operational amplifier

$$V_{out,2} - V_{out,1} = A\left(V_{in,2} - V_{in,1}\right)$$

- A current-mirror (or current-source)



This circuit element can be used to provide steady (quiescent) currents for biasing other transistors (amplifier stages) in integrated circuits (IC's).

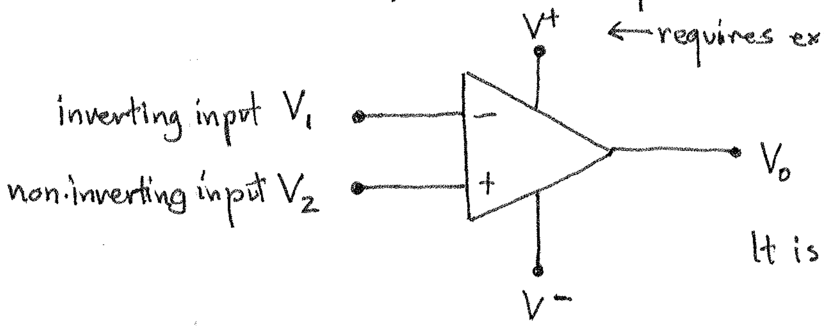
- Integrated Circuits ~~have~~ are fabricated on a single chip. Transistors (BJT or FET) and connecting "wires" are efficiently produced. Resistors and capacitors take up a lot of chip area. So IC designers (engineers) try to replace resistors (especially) with transistors.

- See circuit diagram for the 741 op-amp (Horowitz and Hill, p. 189)

  24 BJT transistors, 11 resistors, 1 capacitor

  (1 capacitor: occupies 13X the chip area of 1 transistor.)

- An ideal operational amplifier



$$V_o = A_o (V_2 - V_1)$$

It is a differential amplifier

(1) Input impedance is very large (ideally infinite)
(2) The "open-loop gain", A_o, is very large (ideally infinite)
(3) The output resistance is very small (ideally zero)
(4) The gain is ideally independent of frequency (infinite bandwidth)
(5) Common-mode gain is very small (ideally zero)

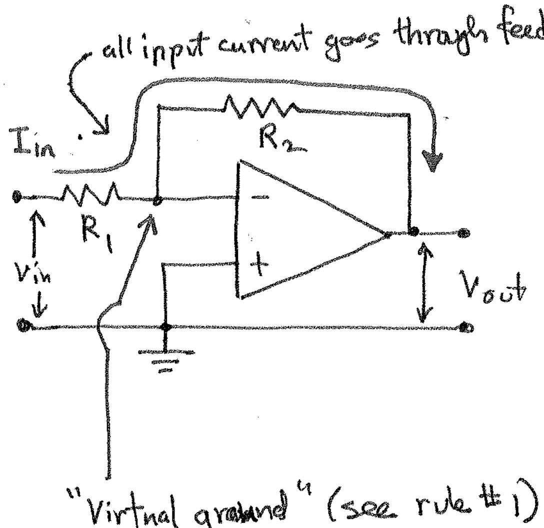
Op amps are almost always used in circuits having negative feedback: A portion of the output signal is returned to the inverting input in order to reduce the input signal $(V_2 - V_1)$.

Golden rules for analyzing op-amp circuits with negative feedback:

(1) $V_1 = V_2$ ... the negative feedback and infinite open loop gain drive the inputs to zero voltage difference

(2) No current flows into/out of the op-amp inputs
A lot of current can flow from/to the output.

- Inverting Amplifier



Kirchoff loop (w/ virtual ground)

$$V_{in} - I_{in}R_1 = 0$$

$$-I_{in}R_2 - V_{out} = 0$$

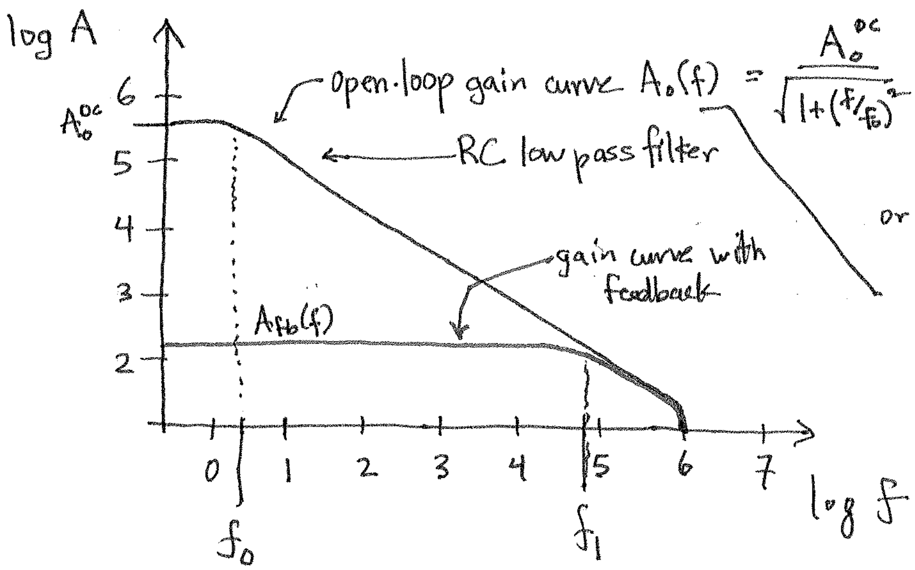
⇓ algebra

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

Input resistance $R_{in} = R_1$

Output resistance $R_{out} \approx 0$ <u>small</u>

Frequency response of Op-Amp Circuits with Negative Feedback



$$A_o(f) = \frac{A_o^{DC}}{\sqrt{1+(f/f_0)^2}} \approx \frac{A_o^{DC} f_o}{f} \qquad f \gg f_o$$

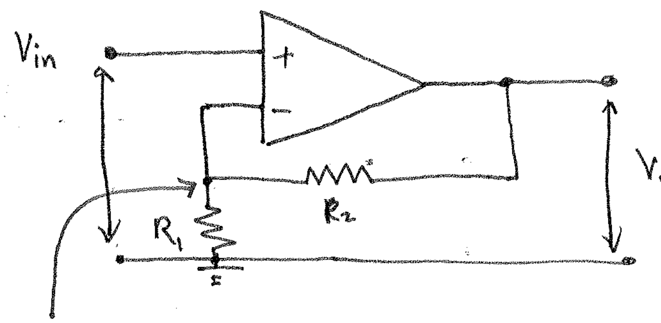
or.. $A_o(f) f = A_o^{DC} f_o$

⇓

$$A_{Fb}(f) \cdot f_1 = A_o^{DC} f_o$$

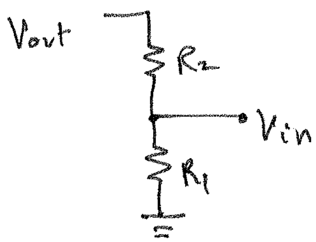
This quantity is called the <u>gain bandwidth product</u> and it is a property of the op amp itself.

- Noninverting Amplifier



By rule #1 this point is $V_1 = V_2 = V_{in}$

V_{in} is related to V_{out} by the voltage divider relation



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

Solve for the gain

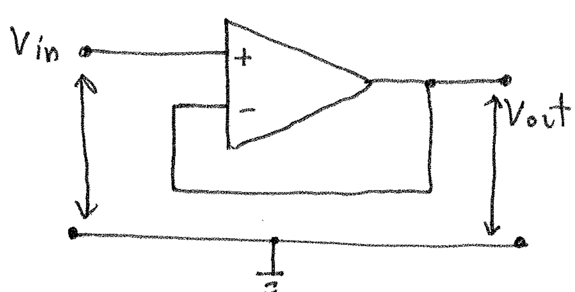
$$\boxed{\frac{V_{out}}{V_{in}} = 1 + \frac{R_2}{R_1}}$$

Input impedance $R_{in} \cong \infty$ large

Output impedance $R_{out} \cong 0$ small

- Voltage Follower (or "Buffer" Amplifier)

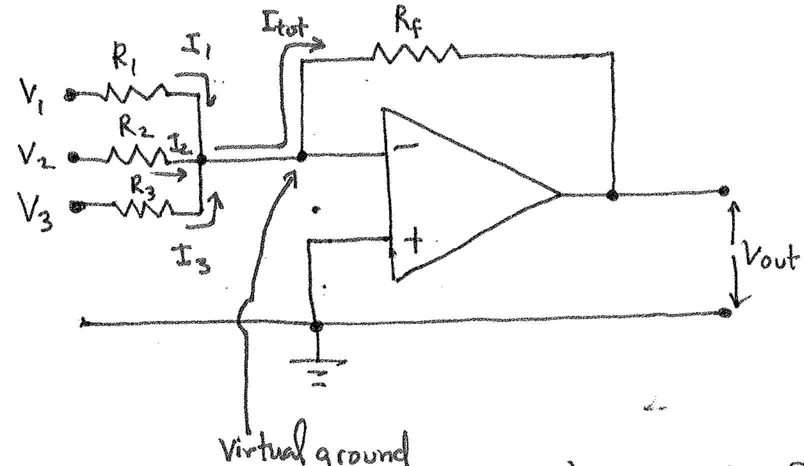
Let $R_2 \to 0$, $R_1 \to \infty$ in the above circuit



$$\boxed{\frac{V_{out}}{V_{in}} = 1}$$

This circuit has high input/low output impedance

- Weighted Summing Amplifier



$I_1 = V_1/R_1$

$I_2 = V_2/R_2$

$I_3 = V_3/R_3$

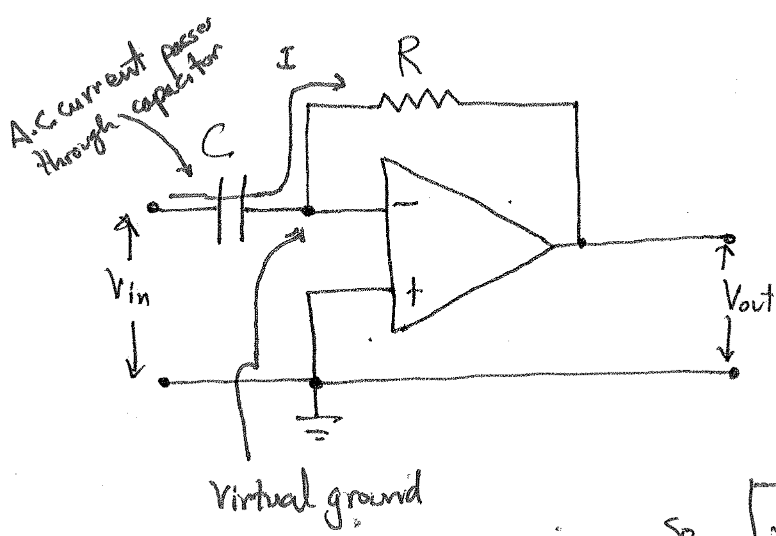
$$I_{tot} = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}$$

$$V_{out} = -I_{tot} R_F$$

or
$$\boxed{V_{out} = -R_f\left[\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right]}$$

If $R_1 = R_2 = R_3$ then $V_{out} = -\frac{R_f}{R_1}\left[V_1 + V_2 + V_3\right]$

- Differentiator



$V_{in} = \frac{Q}{C}$

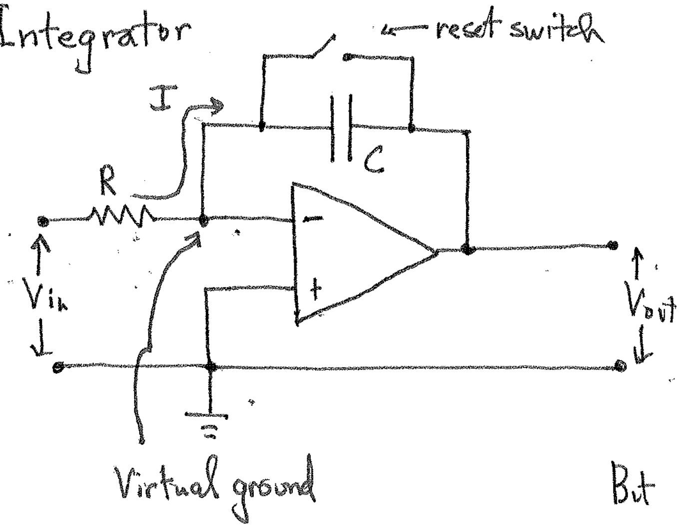
$V_{out} = -IR$

but $I = \frac{dQ}{dt} = C\frac{dV_{in}}{dt}$

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

Output signal looks like minus the derivative of the input signal.

- Integrator



$$V_{in} - IR = 0$$

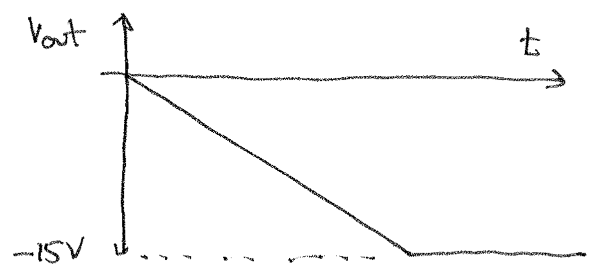
$$V_{out} = -\frac{Q}{C}$$

But $Q = \int I\,dt = \frac{1}{R}\int V_{in}\,dt$

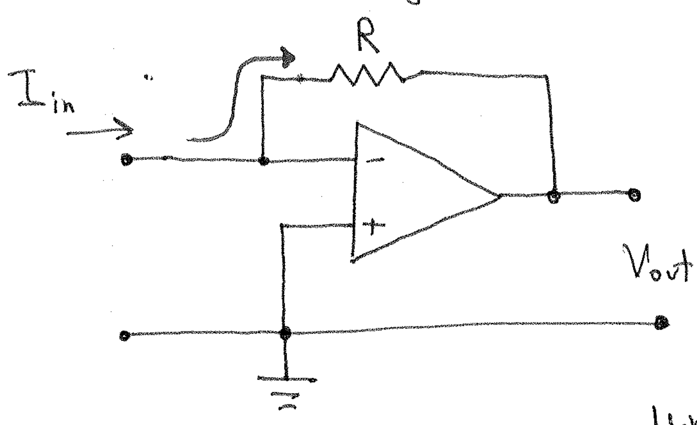
so.. $$\boxed{V_{out} = -\frac{1}{RC}\int V_{in}\,dt}$$

Any small D.C. input offset gets integrated ... until the output reaches the power supply voltage ("the rail"). To discharge the feedback capacitor, include a reset switch ... either push-button (mechanical) or a transistor (probably a FET) that can be reset by an electrical reset signal.

$$V_{out}(t) = -\frac{1}{RC}\,V_{offset}\cdot(t - t_0)$$



- Current-to-Voltage (or "Transimpedance") Amplifier



$$\boxed{V_{out} = -R\,I_{in}}$$

Some "signals" of interest are "current sources". For example, the signal from a photodetector ("photodiode")