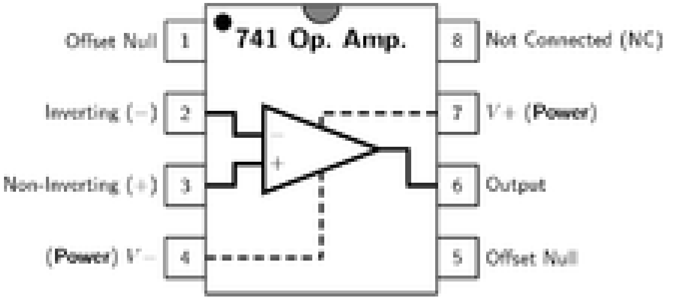
# What is an Op-Amp? – The Surface

- An Operational Amplifier (Op-Amp) is an integrated circuit that uses external voltage to amplify the input through a very high gain.
- We recognize an Op-Amp as a mass-produced component found in countless electronics.

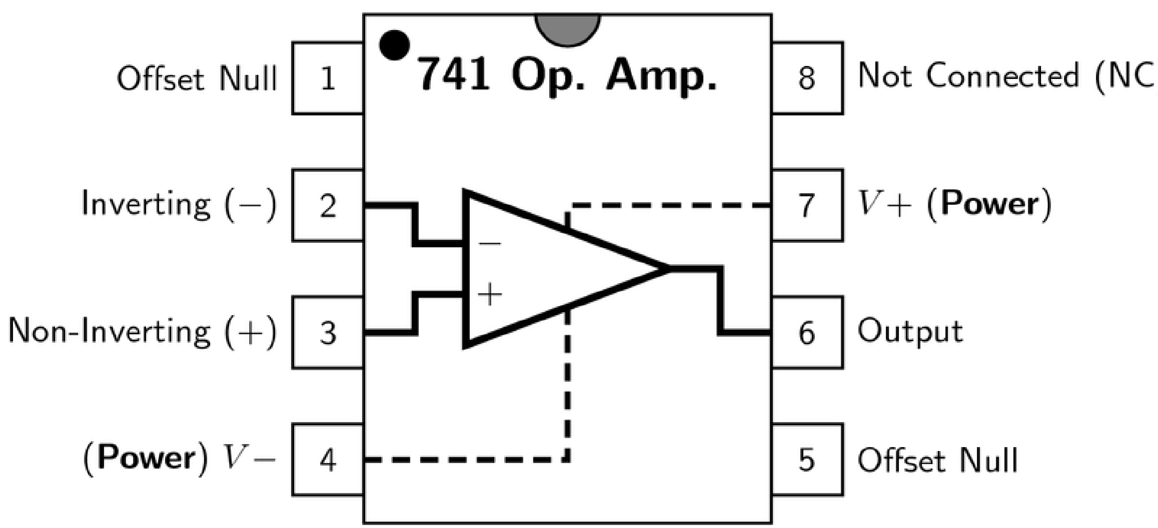

What an Op-Amp looks like to a lay-person




What an Op-Amp looks like to an engineer

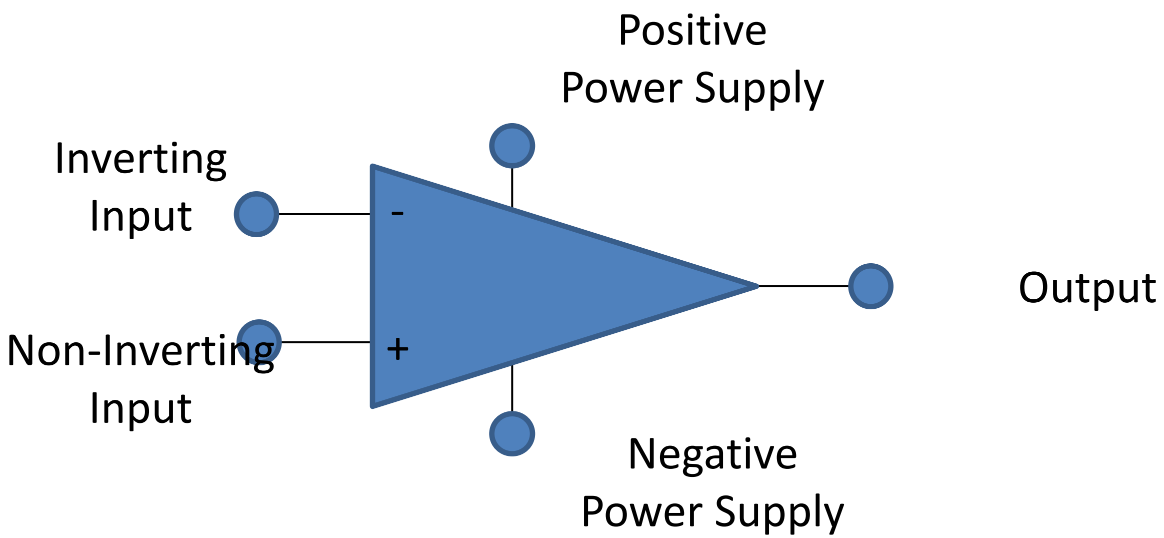
# What is an Op-Amp? – The Layout

- There are 8 pins in a common Op-Amp, like the 741 which is used in many instructional courses.



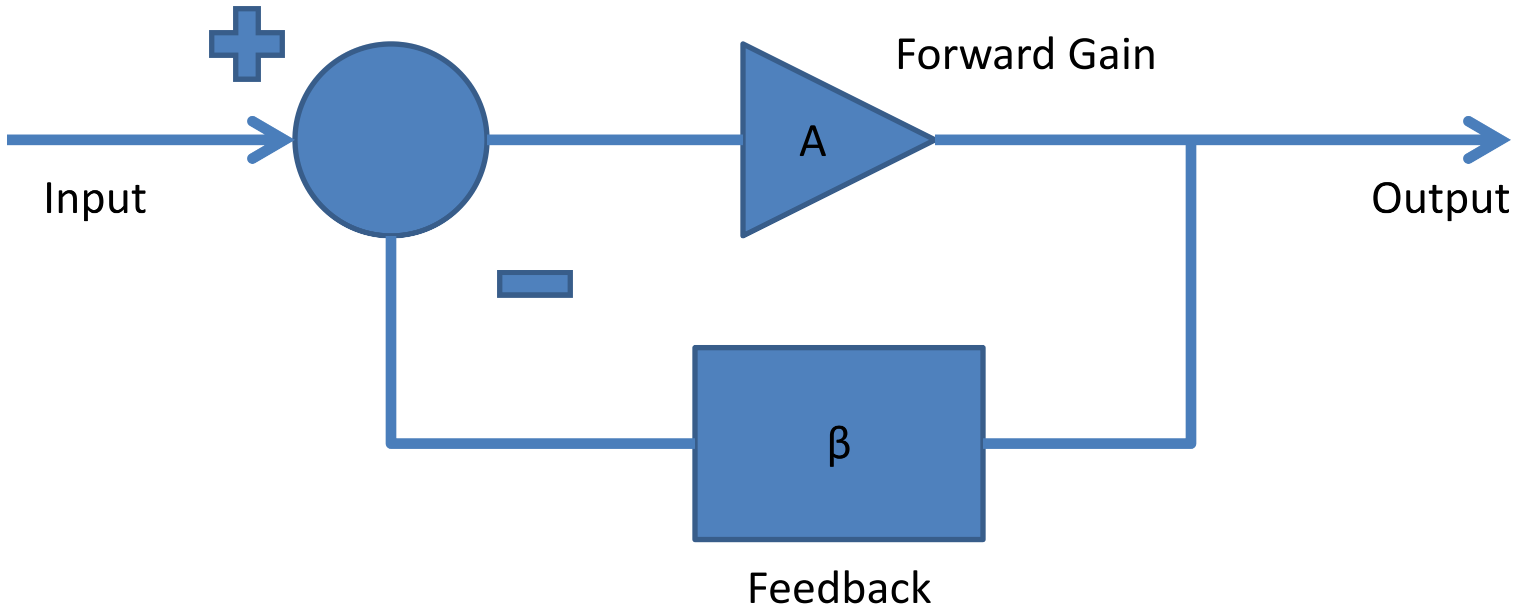
# What is an Op-Amp? – The Inside

- The actual count varies, but an Op-Amp contains several Transistors, Resistors, and a few Capacitors and Diodes.
- For simplicity, an Op-Amp is often depicted as this:



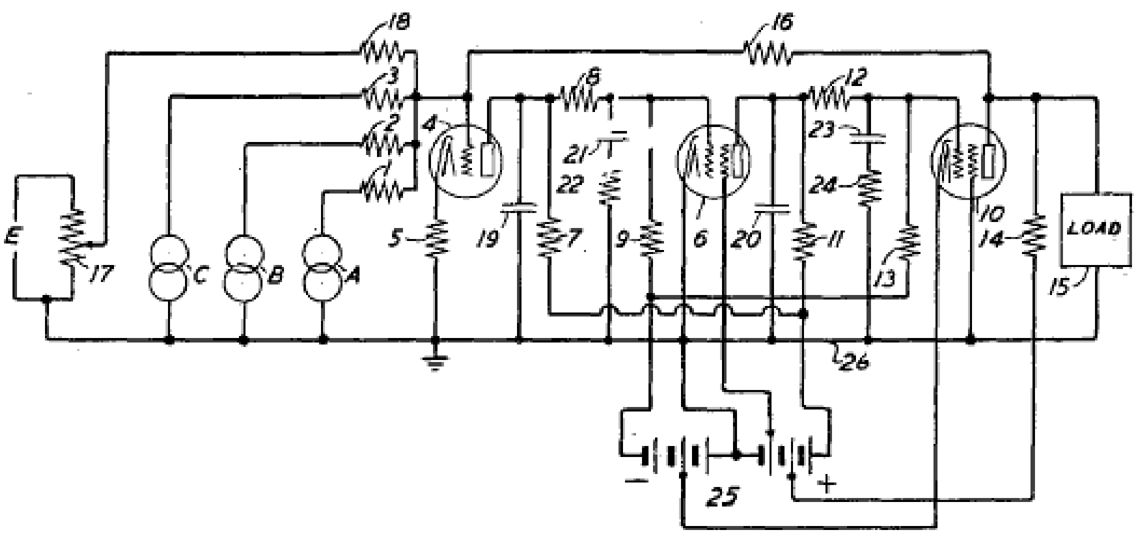
# History of the Op-Amp – The Dawn

- Before the Op-Amp: Harold S. Black develops the feedback amplifier for the Western Electric Company (1920-1930)



# History of the Op-Amp – The Dawn

- **The Vacuum Tube Age**
- The First Op-Amp: (1930 – 1940) Designed by Karl Swartzel for the Bell Labs M9 gun director
- Uses 3 vacuum tubes, only one input, and ± 350 V to attain a gain of 90 dB
- Loebe Julie then develops an Op-Amp with two inputs: Inverting and Non-inverting



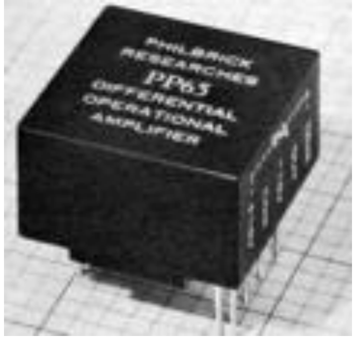
# History of the Op-Amp – The Shift

- The end of Vacuum Tubes was built up during the 1950's-1960's to the advent of solid-state electronics

1. The Transistor
2. The Integrated Circuit
3. The Planar Process

# History of the Op-Amp – The Shift

- 1960s: beginning of the Solid State Op-Amp
- Example: GAP/R P45 (1961 – 1971)
  - Runs on ± 15 V, but costs $118 for 1 – 4
- The GAP/R PP65 (1962) makes the Op-Amp into a circuit component as a potted module



# History of the Op-Amp – The Evolution

- The solid-state decade saw a proliferation of Op-Amps
  - Model 121, High Speed FET family, etc.
- Robert J. Widlar develops the µA702 Monolithic IC Op-Amp (1963) and shortly after the µA709
- Fairchild Semiconductor vs. National Semiconductor
  - National: The LM101 (1967) and then the LM101A (1968) (both by Widlar)
  - Fairchild: The "famous" µA741 (by Dave Fullager 1968) and then the µA748 (1969)

# Mathematics of the Op-Amp

- The gain of the Op-Amp itself is calculated as:

$$G = V_{out}/(V_+ - V_-)$$

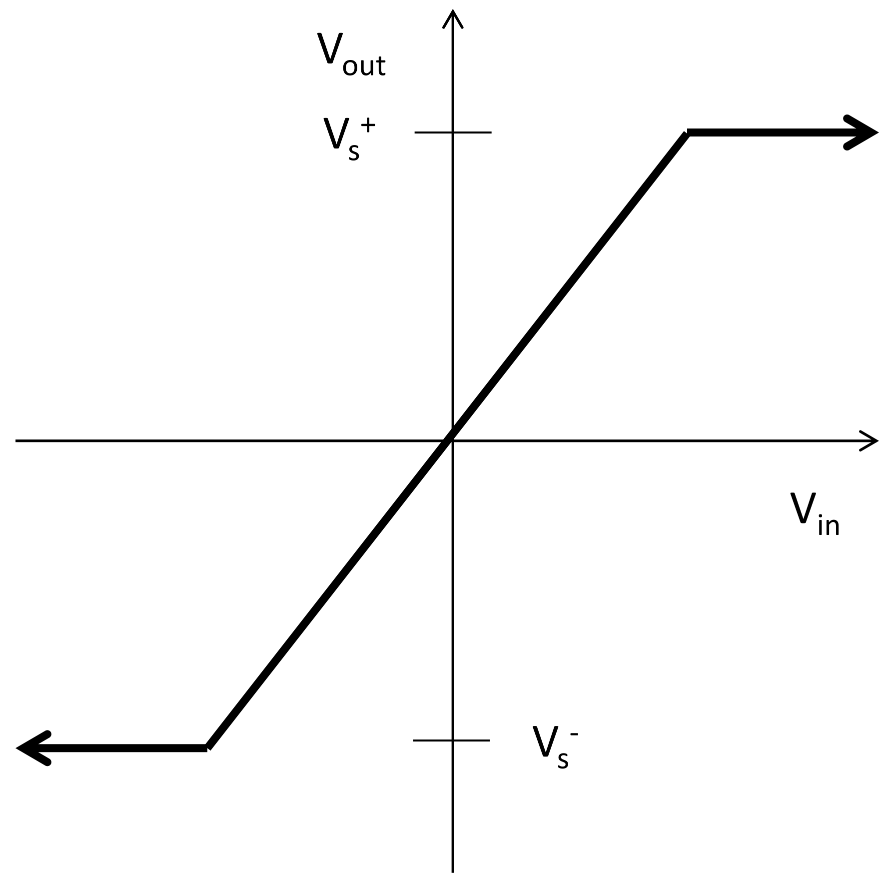
- The maximum output is the power supply voltage

- When used in a circuit, the gain of the circuit (as opposed to the op-amp component) is:

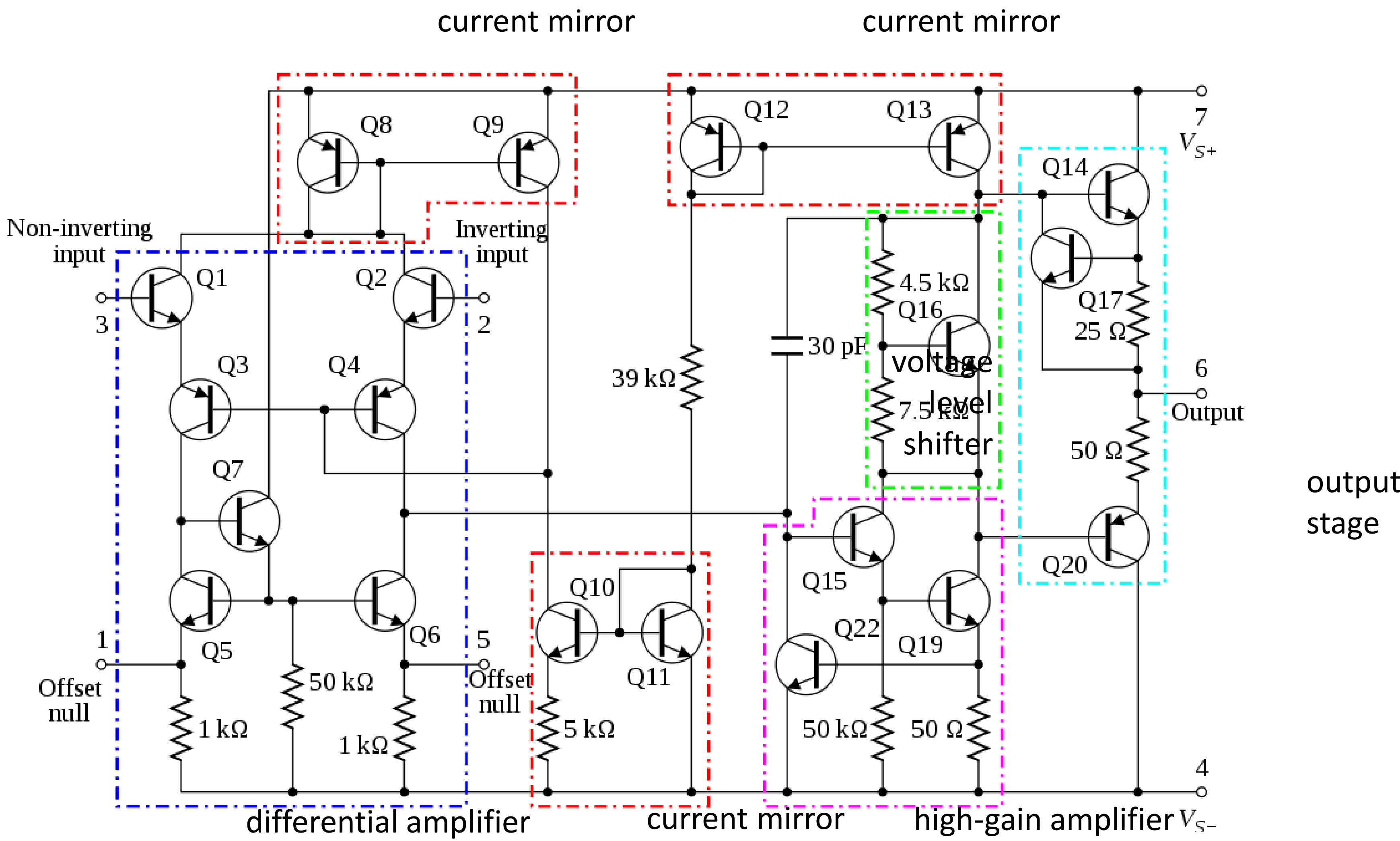
$$A_v = V_{out}/V_{in}$$

# Op-Amp Saturation

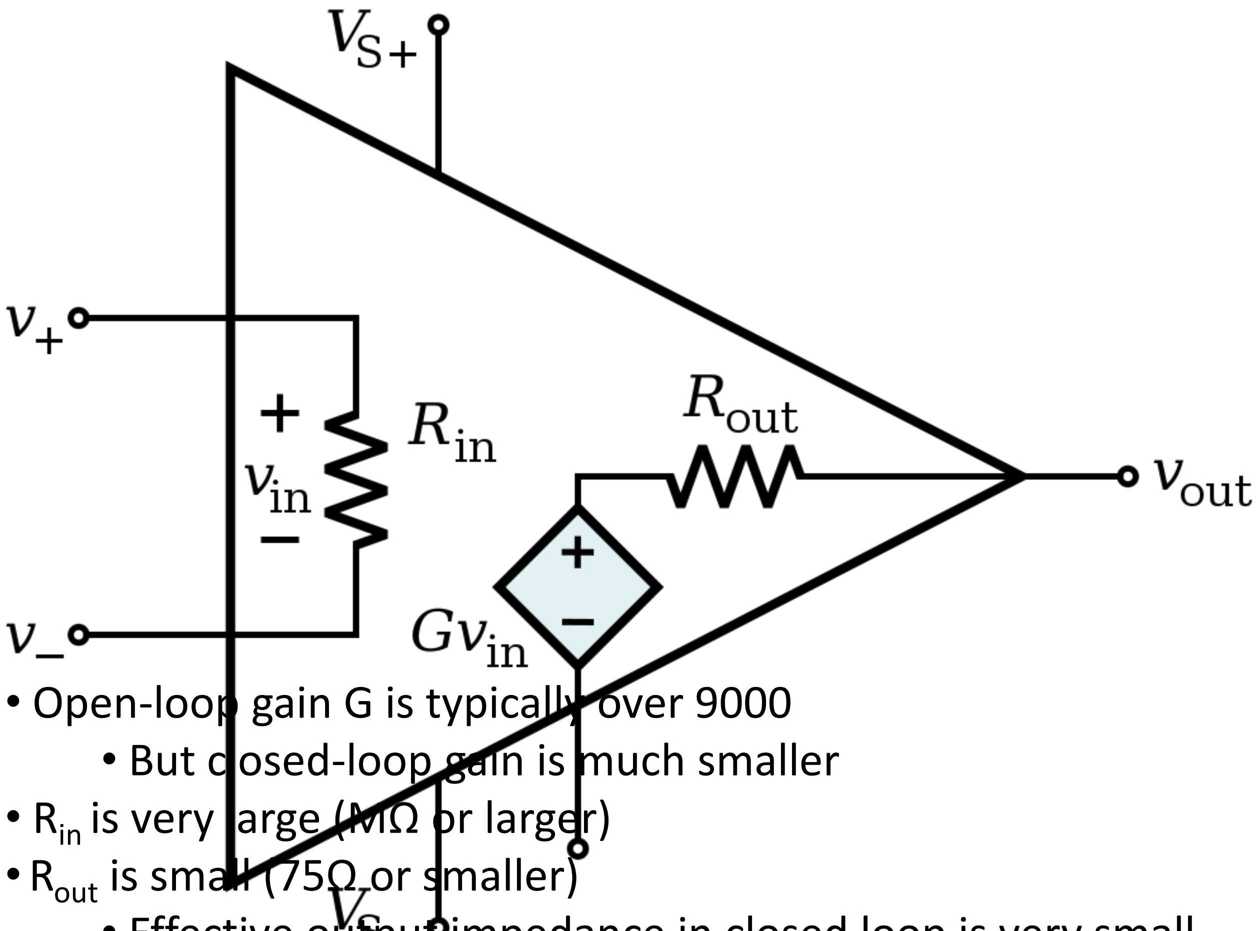
- As mentioned earlier, the maximum output value is the **supply voltage**, positive and negative.
- The gain (G) is the slope between saturation points.



# 741 Op-Amp Schematic

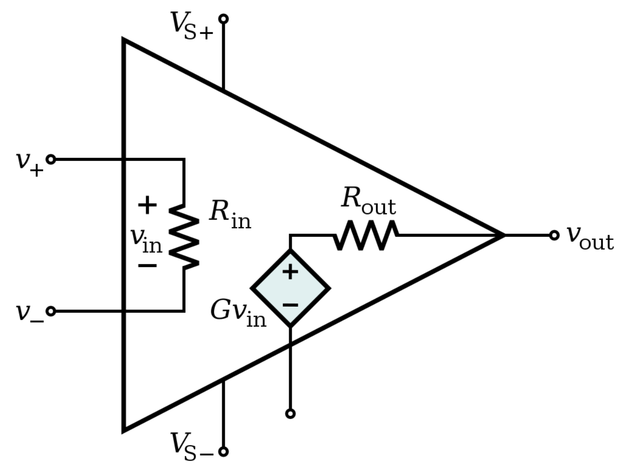


# Op-Amp Characteristics



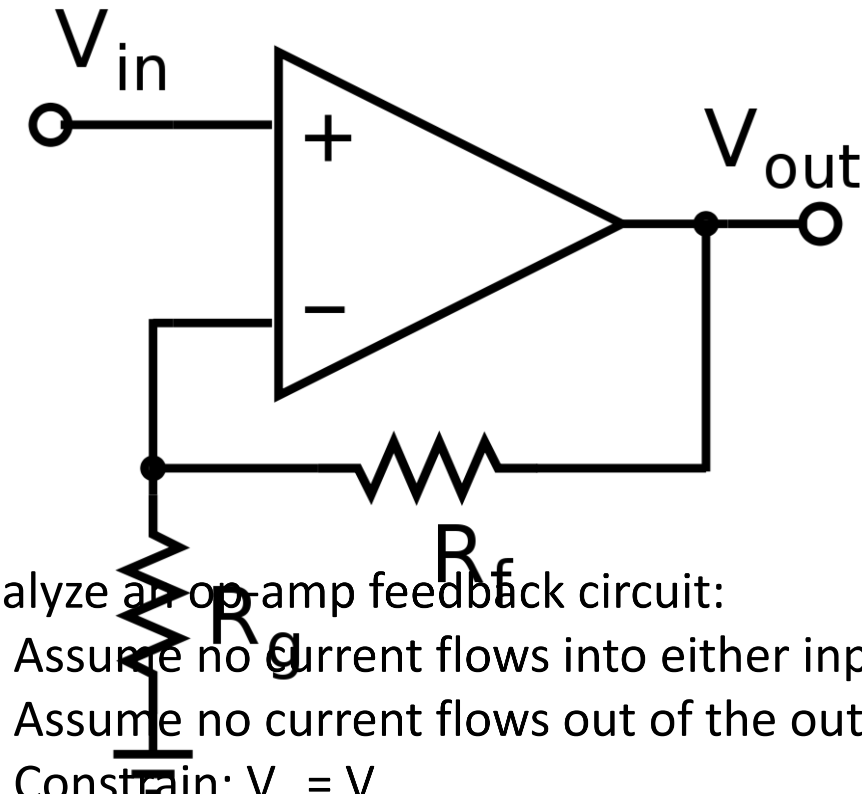

- Open-loop gain G is typically over 9000
  - But closed-loop gain is much smaller
- $R_{in}$ is very large (MΩ or larger)
- $R_{out}$ is small (75Ω or smaller)
  - Effective output impedance in closed loop is very small

# **Ideal** Op-Amp Characteristics




- Open-loop gain G is infinite
- $R_{in}$ is infinite
  - Zero input current
- $R_{out}$ is zero

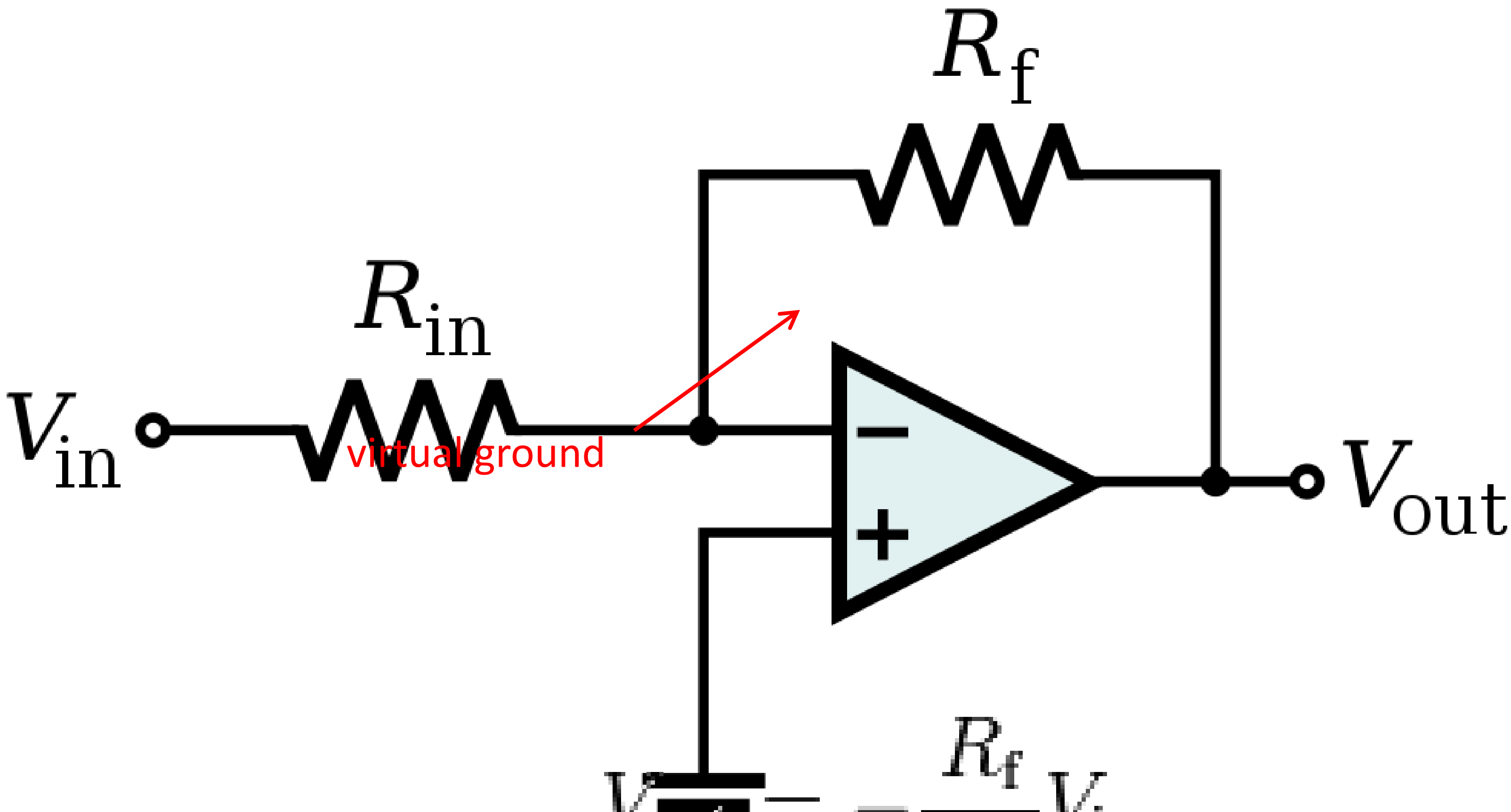
# Ideal Op-Amp Analysis




To analyze an op-amp feedback circuit:

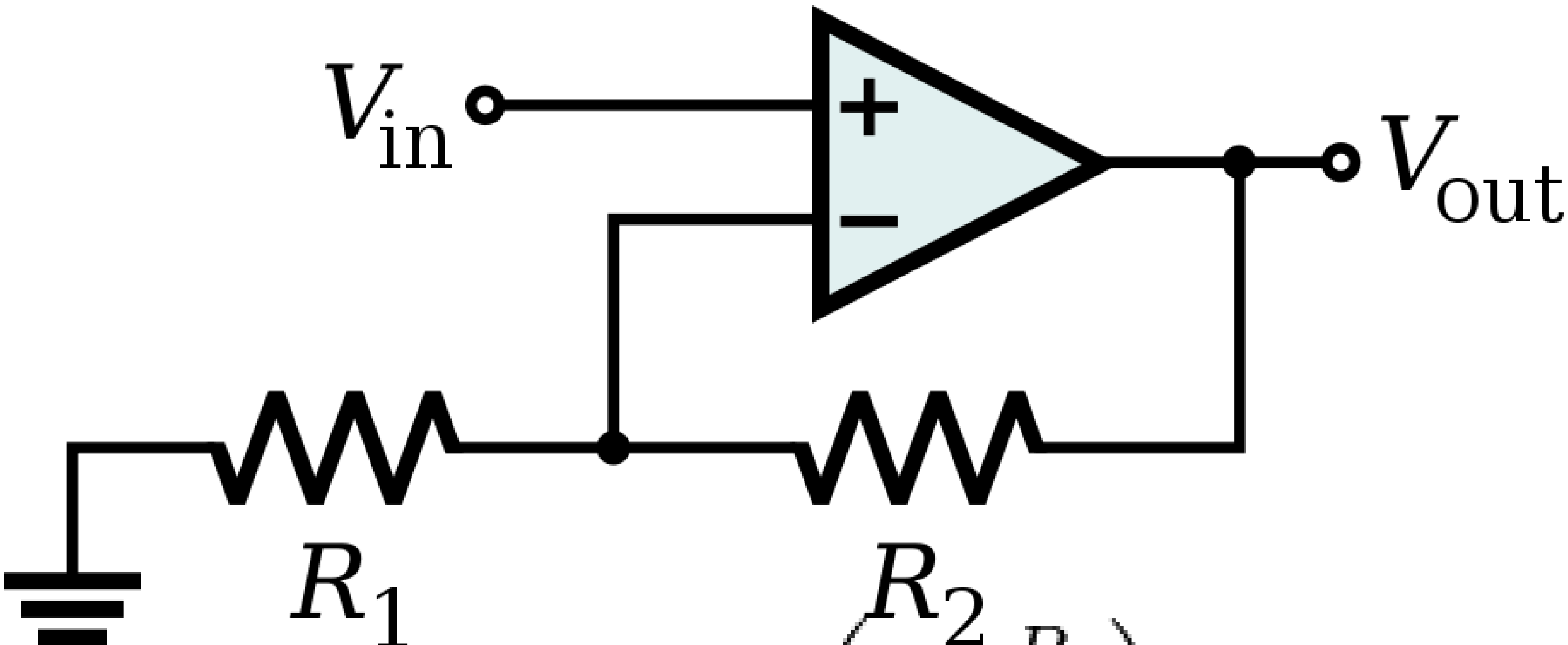
- Assume no current flows into either input terminal
- Assume no current flows out of the output terminal
- Constrain: $V_+ = V_-$

# Inverting Amplifier Analysis



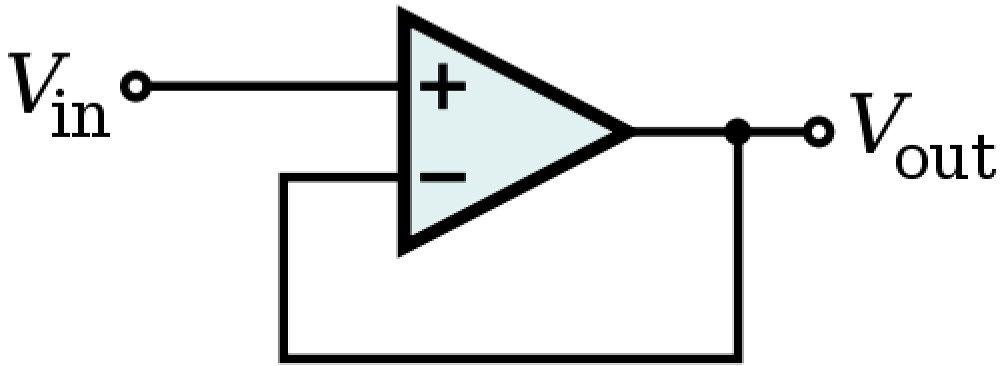

$$V_{out} = -\frac{R_f}{R_{in}} V_{in}$$

# Non-Inverting Amplifier Analysis

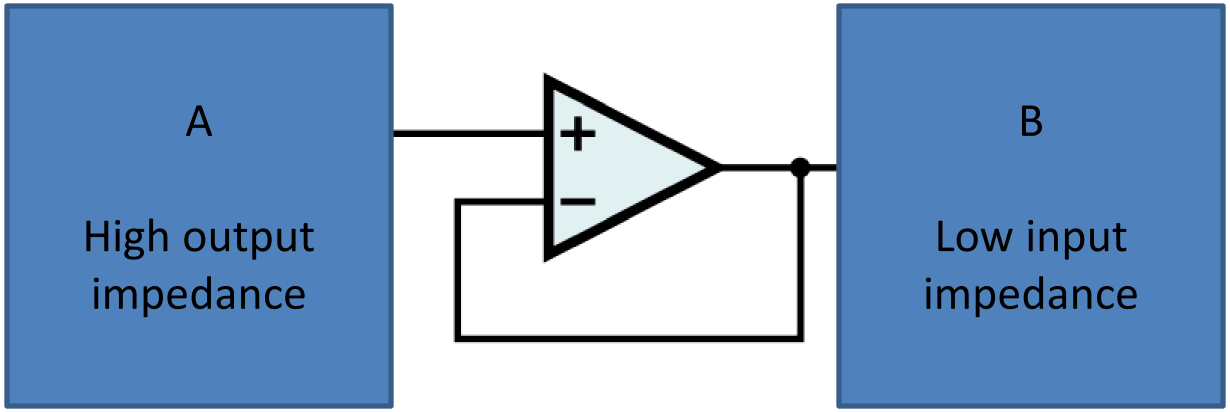



$$V_{\text{out}} = V_{\text{in}} \left( 1 + \frac{R_2}{R_1} \right)$$

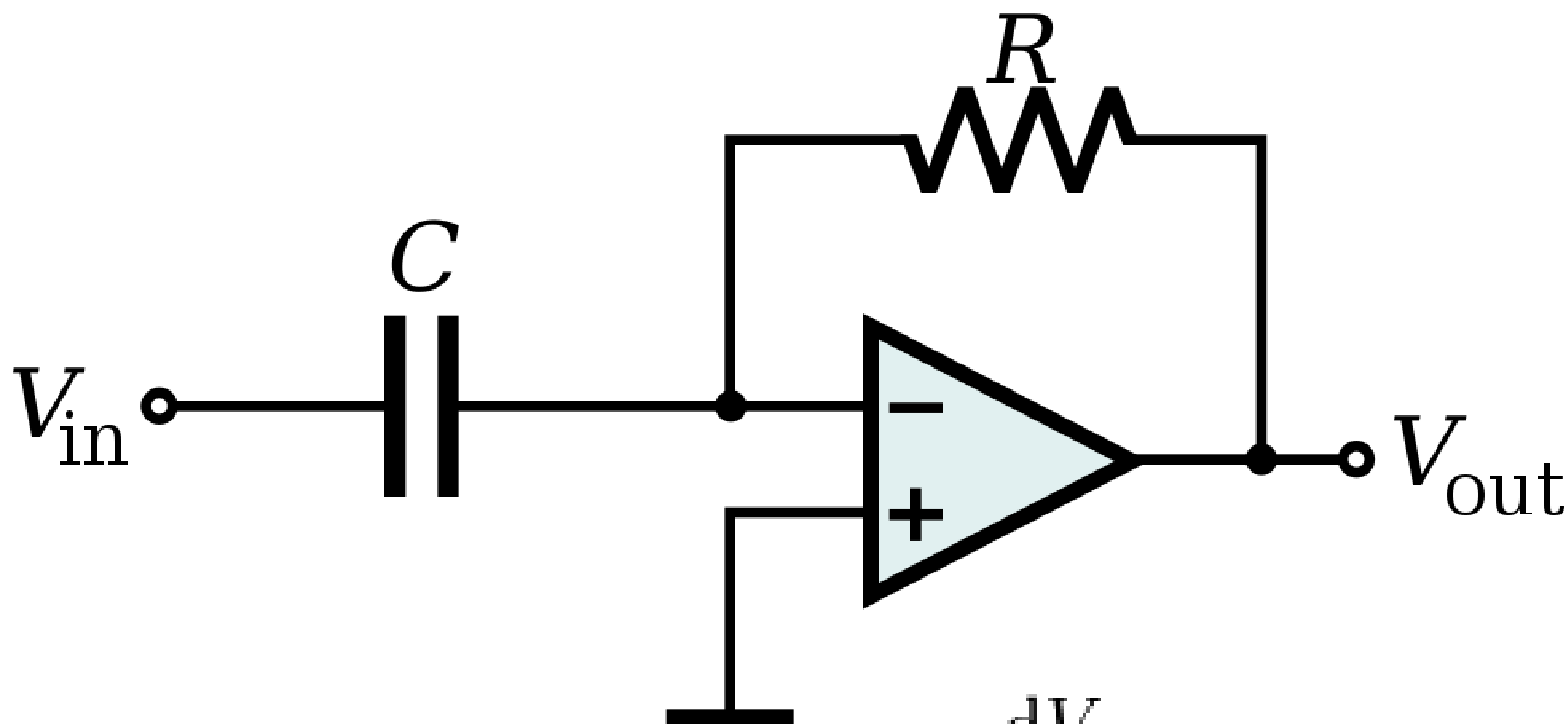
# Op-Amp Buffer




Vout = Vin
Isolates loading effects

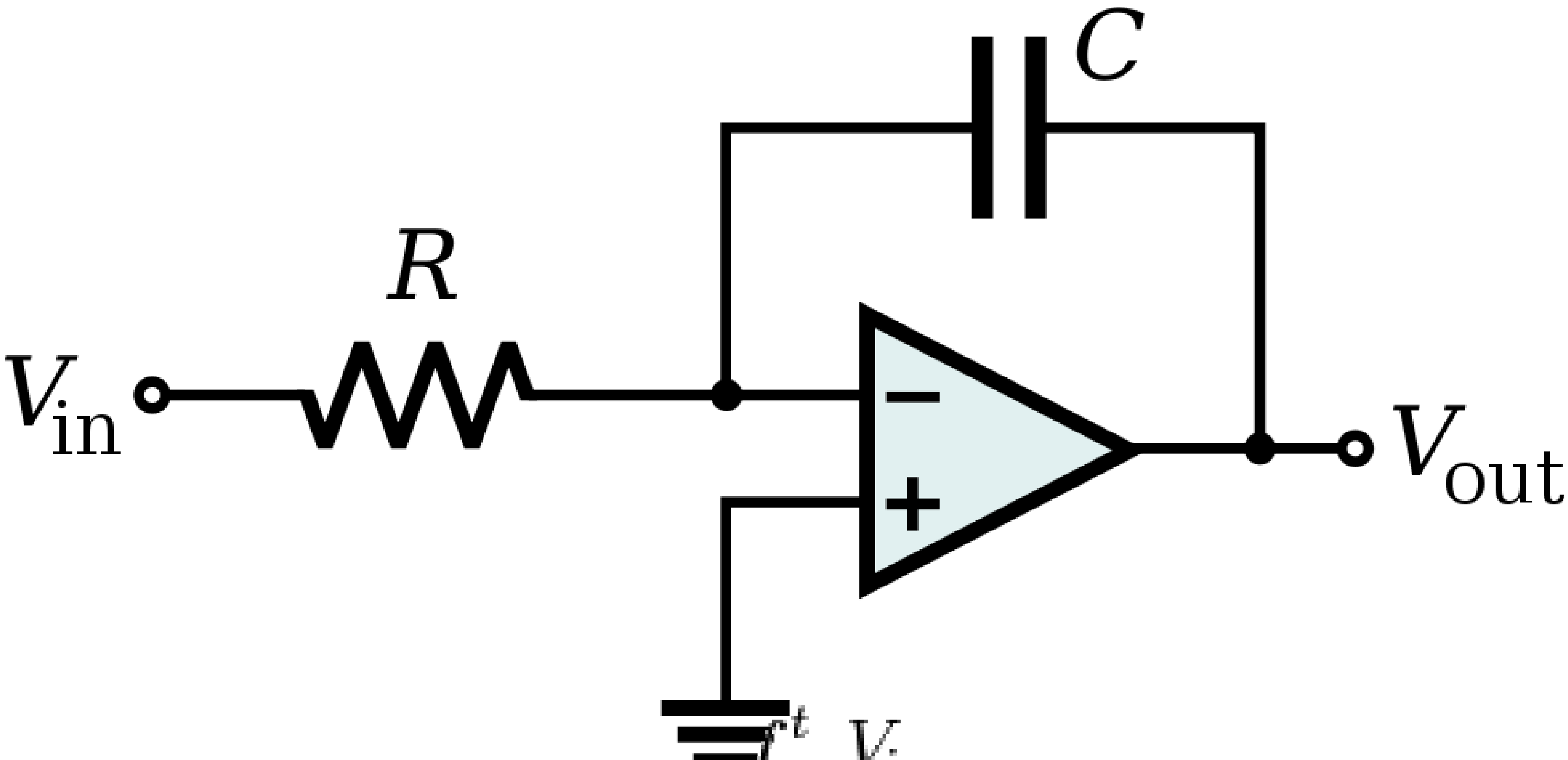


# Op-Amp Differentiator



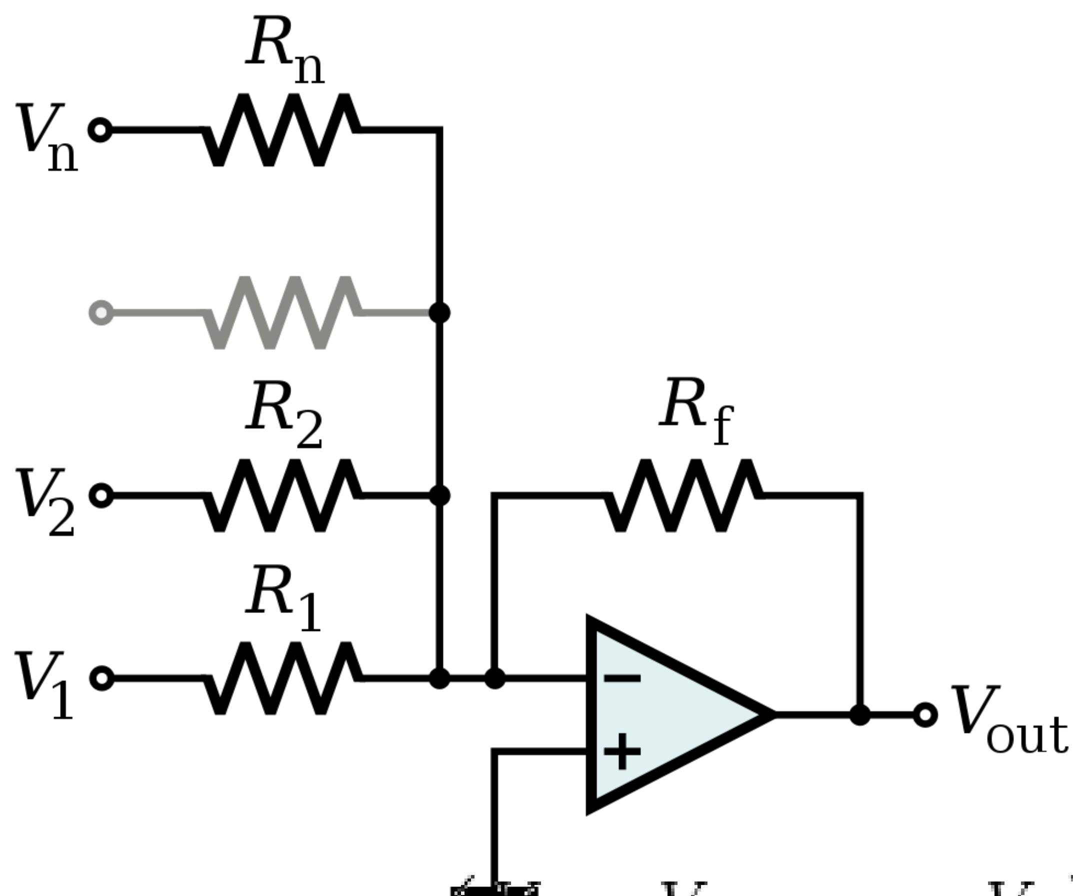

$$V_{\text{out}} = -RC\,\frac{\mathrm{d}V_{\text{in}}}{\mathrm{d}t}$$

# Op-Amp Integrator



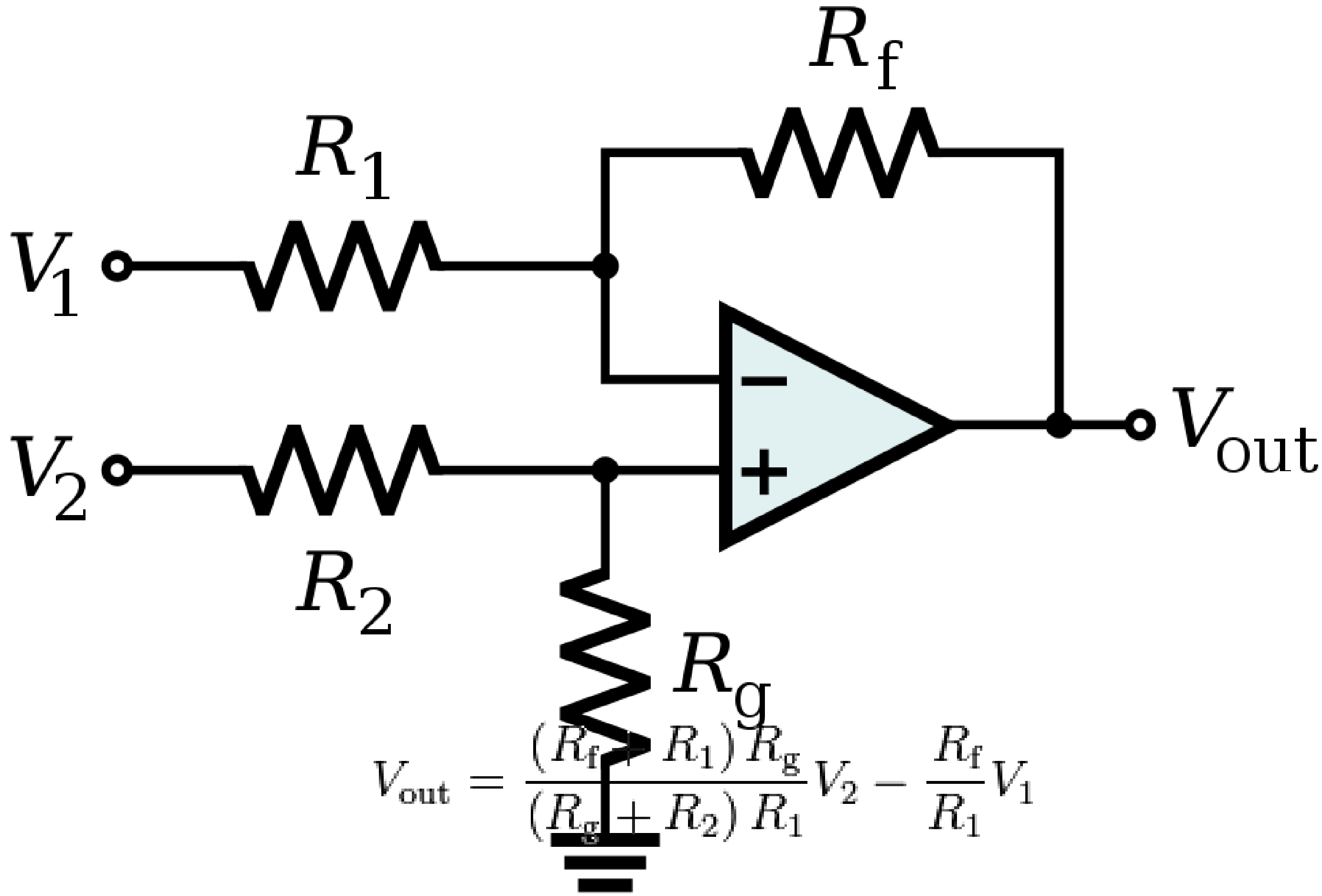

$$V_{\text{out}} = -\int_0^t \frac{V_{\text{in}}}{RC}\,\mathrm{d}t + V_{\text{initial}}$$

# Op-Amp Summing Amplifier




$$V_{\text{out}} = -R_{\text{f}} \left( \frac{V_1}{R_1} + \frac{V_2}{R_2} + \cdots + \frac{V_n}{R_n} \right)$$

# Op-Amp Differential Amplifier




$$V_{\mathrm{out}} = \frac{(R_{\mathrm{f}} + R_1)\,R_{\mathrm{g}}}{(R_{\mathrm{g}} + R_2)\,R_1} V_2 - \frac{R_{\mathrm{f}}}{R_1} V_1$$

If $R_1 = R_2$ and $R_f = R_g$:

$$V_{\mathrm{out}} = \frac{R_{\mathrm{f}}}{R_1}(V_2 - V_1)$$