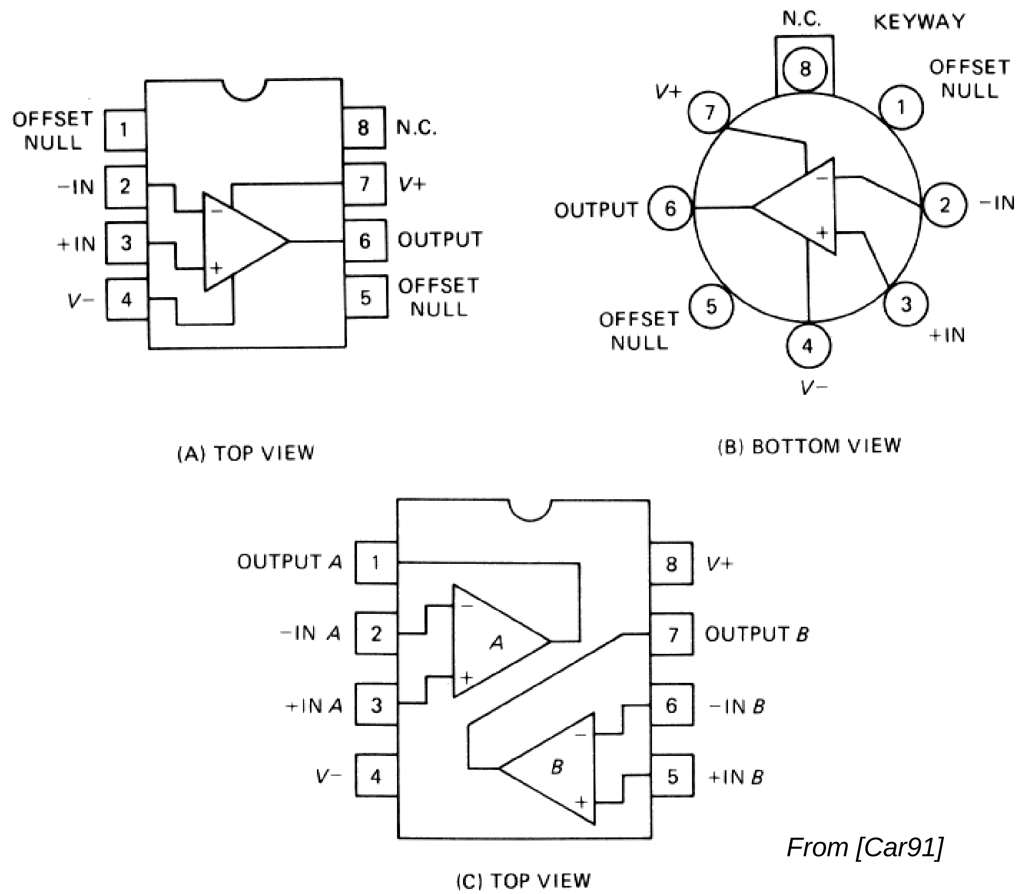
Lecture 5: The ideal operational amplifier

- **The ideal operational amplifier**
  - Terminals
  - Basic ideal op-amp properties
- **Op-amp families**
- **Operational amplifier circuits**
  - Comparator and buffer
  - Inverting and non-inverting amplifier
  - Summing and differential amplifier
  - Integrating and differentiating amplifier
  - Current-voltage conversion

The ideal op-amp

- **Primary op-amp terminals**
  - Inverting input
  - Non-inverting input
  - Output
  - Power supply



From [Car91]

Fig. 12-6 Packaging for industry standard op-amp (741) in (A) DIP and (B) metal can packages; (C) dual op-amp such as 1458 device.

Ideal op-amp characteristics

- **The ideal op-amp is characterized by seven properties**
  - Knowledge of these properties is sufficient to design and analyze a large number of useful circuits
- **Basic op-amp properties**
  - Infinite open-loop voltage gain
  - Infinite input impedance
  - Zero output impedance
  - Zero noise contribution
  - Zero DC output offset
  - Infinite bandwidth
  - Differential inputs that stick together

Ideal Op-Amp Properties

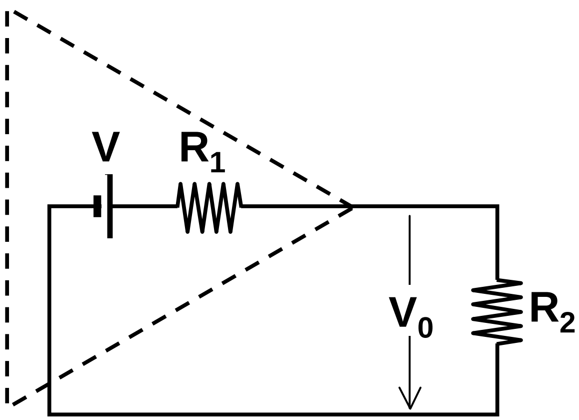
- **Property No.1: Infinite Open-Loop Gain**
  - Open-Loop Gain A_{vol} is the gain of the op-amp without positive or negative feedback
  - In the ideal op-amp A_{vol} is infinite
    - Typical values range from 20,000 to 200,000 in real devices
- **Property No.2: Infinite Input Impedance**
  - Input impedance is the ratio of input voltage to input current

$$Z_{in} = \frac{V_{in}}{I_{in}}$$

  - When Z_{in} is infinite, the input current $I_{in}=0$
    - High-grade op-amps can have input impedance in the TΩ range
      - Some low-grade op-amps, on the other hand, can have mA input currents

Ideal Op-Amp Properties

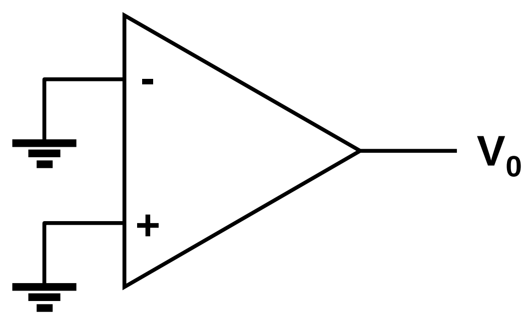
- **Property No. 3: Zero Output Impedance**
  - The ideal op-amp acts as a perfect internal voltage source with no internal resistance
    - This internal resistance is in series with the load, reducing the output voltage available to the load
    - Real op-amps have output-impedance in the 100-20Ω range
  - Example



$$V_0 = \frac{VR_2}{R_1 + R_2}$$

Ideal Op-Amp Properties

- **Property No.4: Zero Noise Contribution**
  - In the ideal op-amp, zero noise voltage is produced internally
    - This is, any noise at the output must have been at the input as well
  - Practical op-amp are affected by several noise sources, such as resistive and semiconductor noise
    - These effects can have considerable effects in low signal-level applications
- **Property No. 5: Zero output Offset**
  - The output offset is the output voltage of an amplifier when both inputs are grounded
  - The ideal op-amp has zero output offset, but real op-amps have some amount of output offset voltage



Ideal Op-Amp Properties

- **Property No. 6: Infinite Bandwidth**
  - The ideal op-amp will amplify all signals from DC to the highest AC frequencies
  - In real opamps, the bandwidth is rather limited
    - This limitation is specified by the Gain-Bandwidth product (GB), which is equal to the frequency where the amplifier gain becomes unity
    - Some op-amps, such as the 741 family, have very limited bandwidth of up to a few KHz
- **Property No. 7: Differential Inputs Stick Together**
  - In the ideal op-amp, a voltage applied to one input also appears at the other input

Operational amplifier types

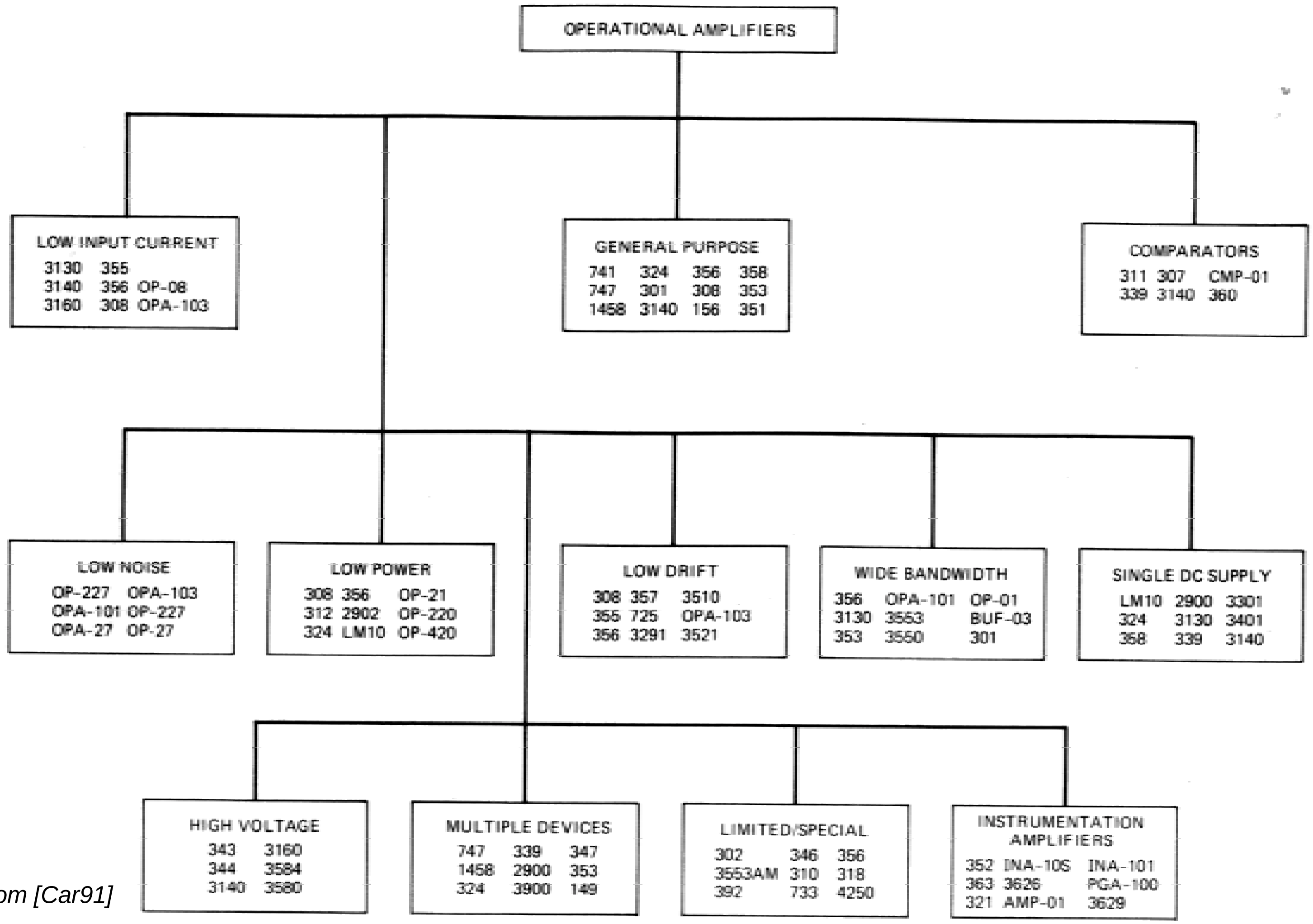
- **General-Purpose Op-Amps**
  - These devices are designed for a very wide range of applications
    - These op-amps have limited bandwidth but in return have very good stability (they are called frequency compensated)
      - Non-compensated op-amps have wider frequency response but have a tendency to oscillate
- **Voltage Comparators**
  - These are devices that have no negative feedback networks and therefore saturate with very low (μV) input signal voltages
    - Used to compare signal levels of the inputs
- **Low Input Current Op-Amps**
  - Op-amps with very low (pico-amp) input currents, as opposed to μA or mA input currents found in other devices
- **Low Noise Op-Amps**
  - Optimized to reduce internal noise
    - Typically employed in the first stages of amplification circuits
- **Low Power Op-Amps**
  - Optimized for low power consumption
    - These devices can operate at low power-supply voltages (I.e., $\pm$1.5VDC)
- **Low Drift Op-Amps**
  - Internally compensated to minimize drift caused by temperature
    - Typically employed in instrumentation circuits with low-level input signals

Operational amplifier types

- **Wide Bandwidth Op-Amps**
  - These devices have a very high GB product (i.e., 100MHz) compared to 741-type op-amps (0.3-1.2MHz)
    - These devices are sometimes called **video op-amps**
- **Single DC Supply Op-Amps**
  - Devices that operate from a monopolar DC power supply voltage
- **High-Voltage Op-Amps**
  - Devices that operate at high DC power supply voltages (i.e. ±44VDC) compared to most other op-amps (±6V to ±22V)
- **Multiple Devices**
  - Those that have more than one op-amp in the same package (i.e., dual or quad op-amps)
- **Instrumentation Op-Amps**
  - These are DC differential amplifiers made with 2-3 internal op-amps
    - Voltage gain is commonly set with external resistors

Families of operational amplifiers

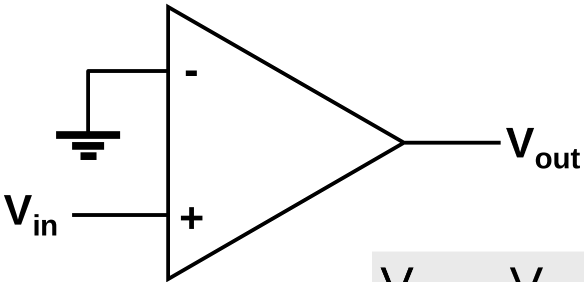
Table 12-1
Families of Operational Amplifiers



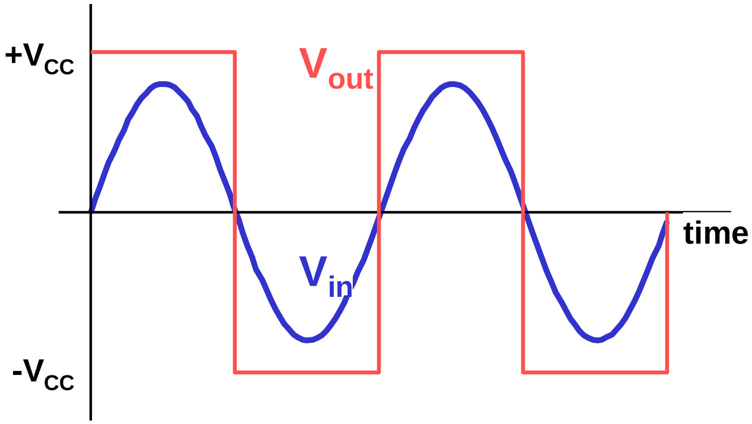
From [Car91]

Op-amp practical circuits

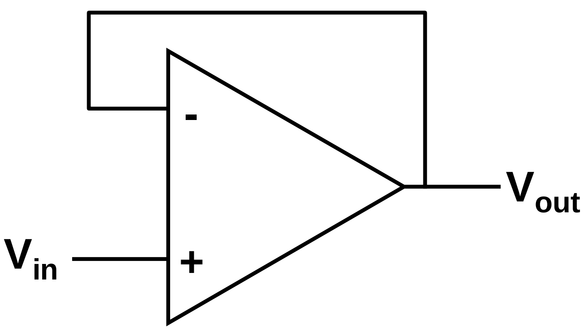
- **Voltage comparator**



$$V_{out} = V_{CC}\,\mathrm{sign}(V_{in})$$



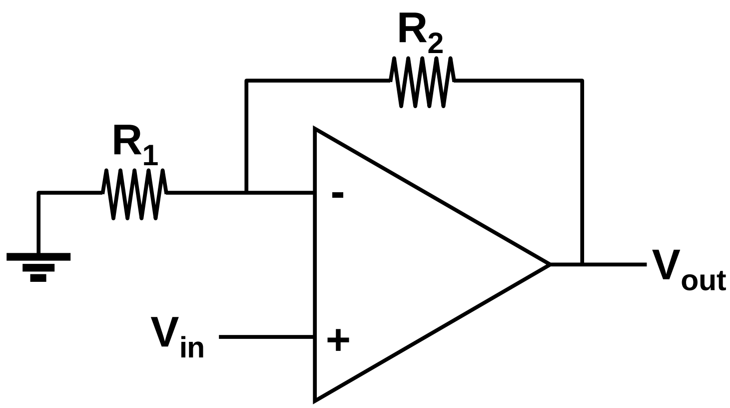
- **Voltage follower**
  - What is the main use of this circuit?
    - Buffering



$$V_{out} = V_{in}$$

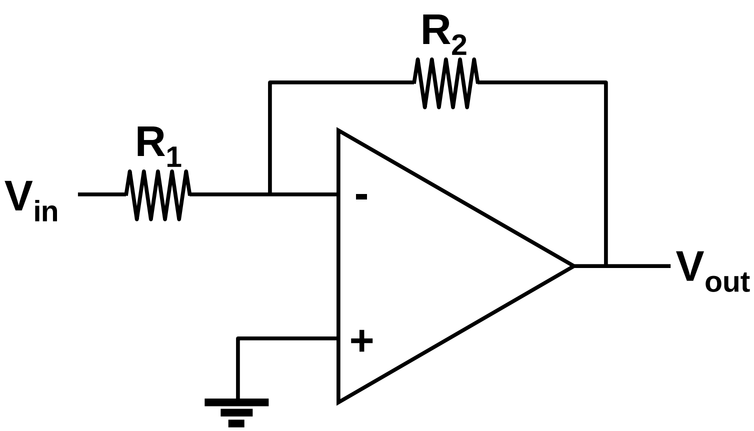
Inverting and non-inverting amplifiers

- **Non-inverting amplifier**



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

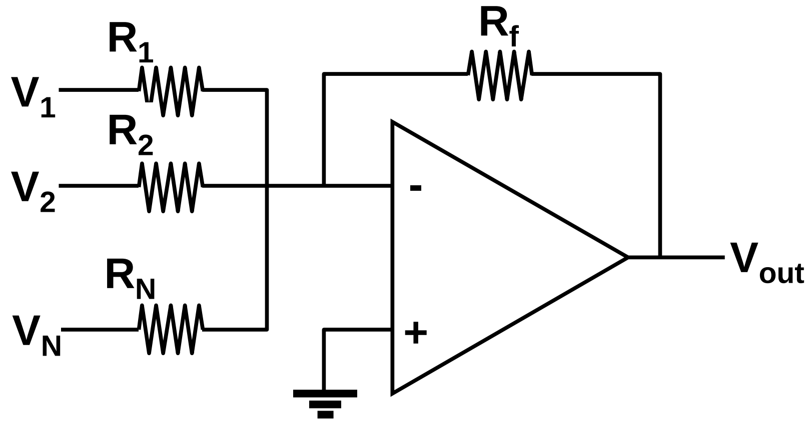
- **Inverting amplifier**



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

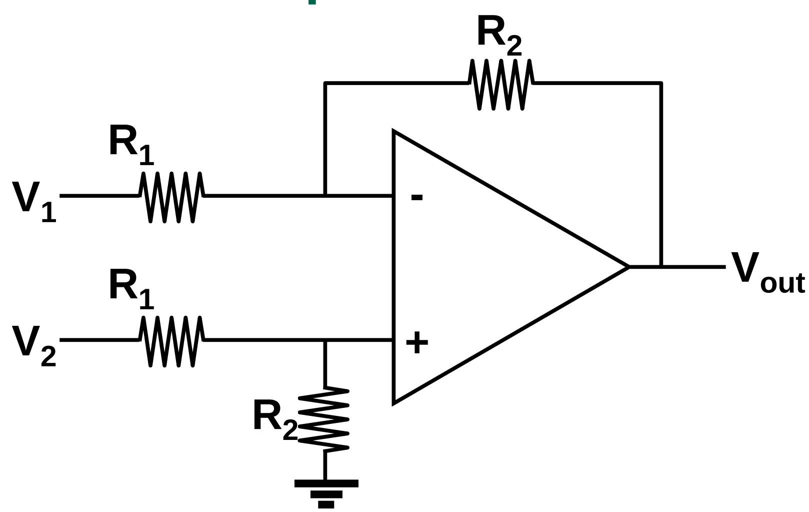
Summing and differential amplifier

- **Summing amplifier**



$$V_{out} = -\left(V_1 \frac{R_f}{R_1} + V_2 \frac{R_f}{R_2} + \cdots + V_N \frac{R_f}{R_N} \right)$$

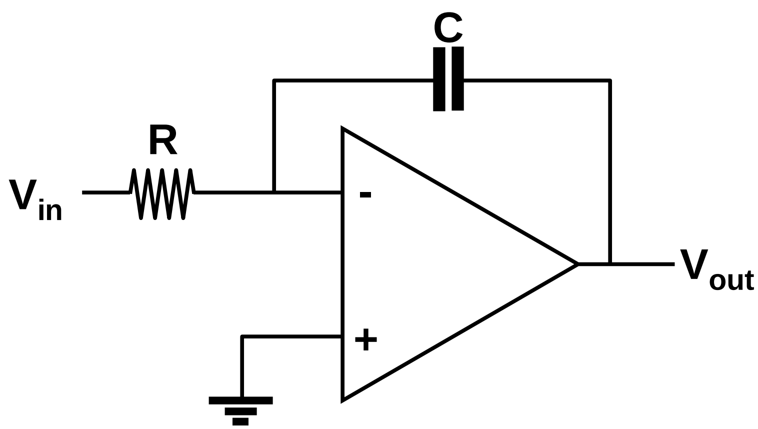
- **Differential amplifier**



$$V_{out} = \frac{R_2}{R_1}(V_2 - V_1)$$

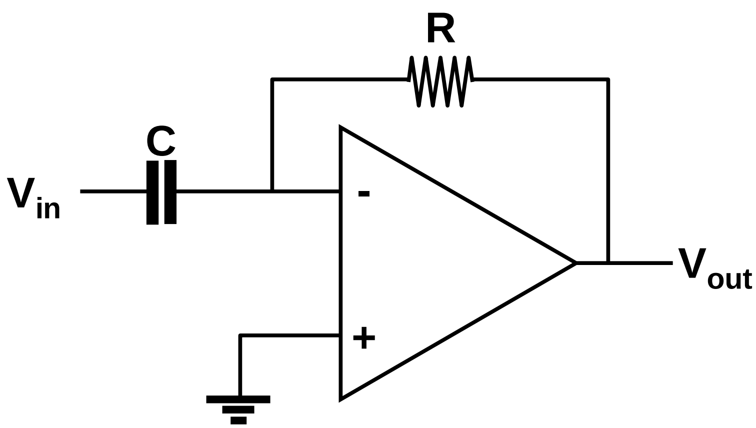
Integrating and differentiating amplifier

- **Integrating amplifier**



$$V_{out} = -\frac{1}{j\omega CR} V_{in} = -\frac{1}{RC}\int V_{in} dt$$

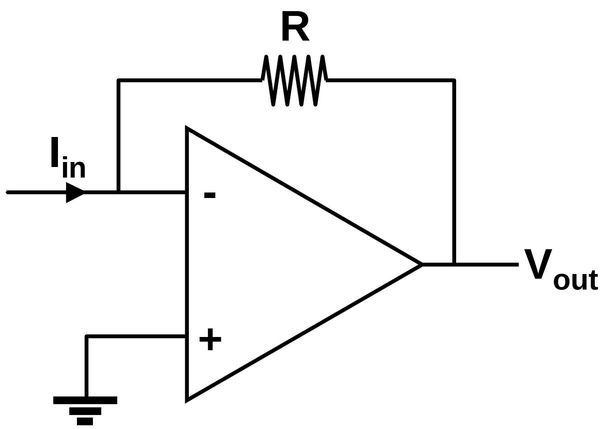
- **Differentiating amplifier**



$$V_{out} = -\frac{R}{\frac{1}{j\omega C}} V_{in} = -RC\frac{dV_{in}}{dt}$$

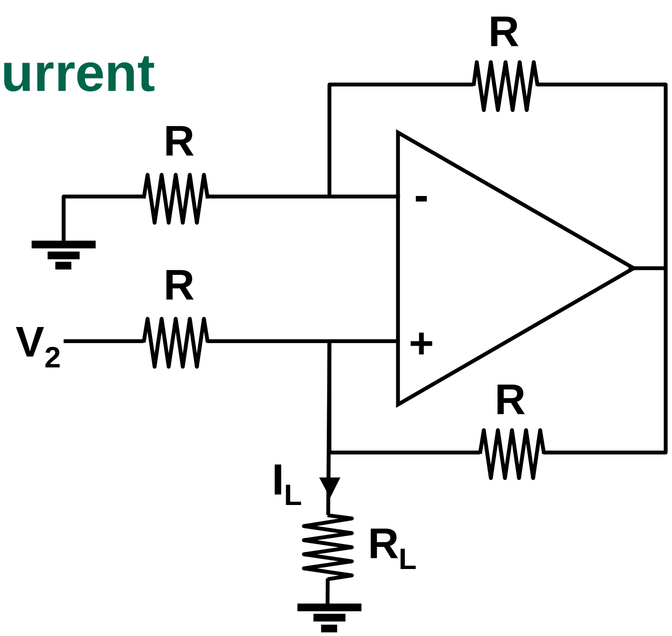
Current to voltage conversion

- **Current-to-voltage**



$$V_{out} = -I_{in}R$$

- **Voltage to current**



$$I_L = \frac{V_{in}}{R}$$

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