Interfacing Circuits

- Measurement of resistance
  - Voltage dividers
  - Wheatstone Bridge
  - Temperature compensation for strain gauges
- AC bridges
  - Measurement of capacitance
  - Measurement of impedance

Capacitors and inductors

- A capacitor is an element capable of storing charge
  - The amount of charge is proportional to the voltage across the capacitor

$$Q = CV$$

  - C is known as the capacitance (measured in Farads)
  - Taking derivatives

$$\frac{dQ}{dt} = \frac{d(CV)}{dt} \Rightarrow I = C\frac{dV}{dt}$$

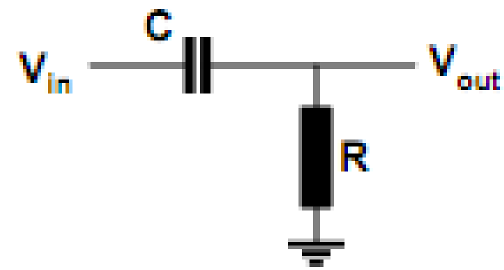
  - Therefore, a capacitor is an element whose rate of voltage change is proportional to the current through it
- Similarly, an inductor is an element whose rate of current change is proportional to the voltage applied across it

$$V = L\frac{dI}{dt}$$

  - L is called the inductance and is measured in Henrys

High Pass Filter

- **High pass filter**
  - The current through cap and resistor is



$$I = \frac{V_{in}}{Z} = \frac{V_{in}}{R + \frac{1}{j\omega C}}$$

  - The output voltage is equal to the voltage differential across the resistor

$$V_{out} = RI = R\frac{V_{in}}{R + \frac{1}{j\omega C}}$$

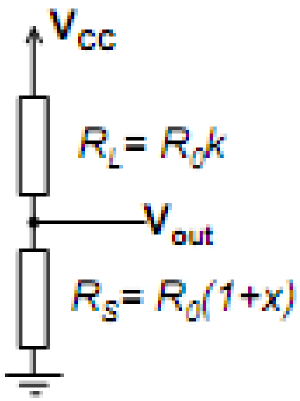
  - If we focus on amplitude and ignore phase

$$|V_{out}| = R\frac{|V_{in}|}{\left|R + \frac{1}{j\omega C}\right|} = R\frac{|V_{in}|}{\sqrt{R^2 + \left(\frac{1}{\omega C}\right)^2}} = |V_{in}|\frac{\omega RC}{\sqrt{(\omega RC)^2 + 1}}$$

    - Asymptotic behavior…
    - Corner frequency $\omega_{CORNER} = \frac{1}{RC} \Rightarrow 20\log_{10}\frac{|V_{out}|}{|V_{in}|} = 20\log_{10}\frac{1}{\sqrt{1+1}} = -3.010\,dB$

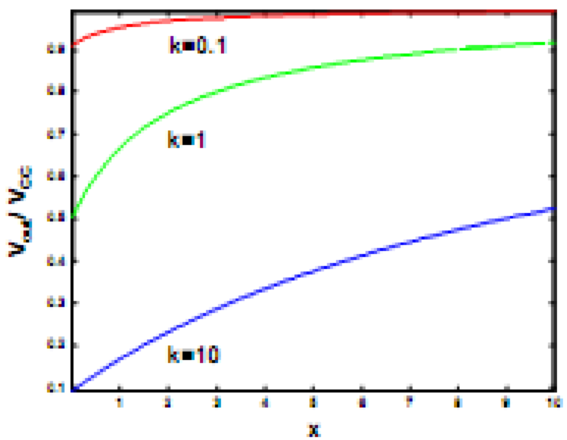
Voltage divider

- Assumptions
  - Interested in measuring the fractional change in resistance x of the sensor: $R_S = R_0(1+x)$
    - R0 is the sensor resistance in the absence of a stimuli
  - Load resistor expressed as RL=R0k for convenience
- The output voltage of the circuit is



$$V_{out} = V_{CC}\frac{R_S}{R_S + R_L} = $$

$$= V_{CC}\frac{R_0(1+x)}{R_0(1+x)+R_0 k} = V_{CC}\frac{1+x}{1+x+k}$$



Questions

What if we reverse R_S and R_L?

How can we recover R_S from V_{out}?

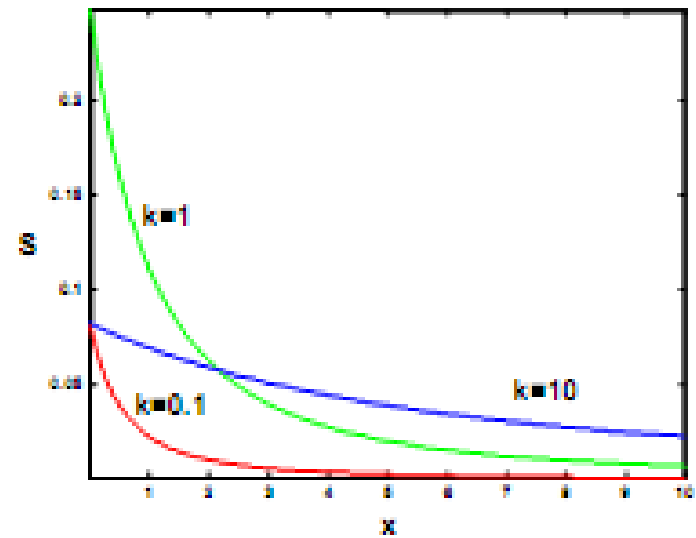
Voltage Divider

- **What is the sensitivity of this circuit?**

$$S = \frac{dV_{out}}{dx} = \frac{d}{dx}\left(V_{CC}\frac{1+x}{1+x+k}\right) =$$

$$= V_{CC}\frac{(1+x+k)-(1+x)}{(1+x+k)^2} =$$

$$= V_{CC}\frac{k}{(1+x+k)^2}$$



- **For which R_L do we achieve maximum sensitivity?**

$$\frac{dS}{dk} = 0 \Rightarrow \frac{d}{dk}\left(V_{CC}\frac{k}{(1+x+k)^2}\right) = 0 \Rightarrow \frac{(1+x+k)^2 - k2(1+x+k)}{(1+x+k)^2} = 0 \Rightarrow \mathbf{k = 1 + x}$$

  - This is, the sensitivity is maximum when $R_L = R_S$

Wheatstone bridge

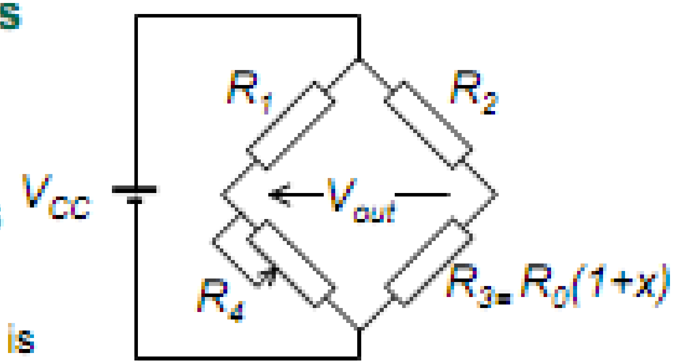
- **A circuit that consists of two dividers**
  - A reference voltage divider (left)
  - A sensor voltage divider
- **Wheatstone bridge operating modes**
  - Null mode
    - R_4 adjusted until the balance condition is met:

$$V_{out} = 0 \Leftrightarrow R_3 = R_4 \frac{R_2}{R_1}$$

      - Advantage: measurement is independent of fluctuations in V_{CC}
  - Deflection mode
    - The unbalanced voltage V_{out} is used as the output of the circuit

$$V_{out} = V_{CC}\left(\frac{R_3}{R_2 + R_3} - \frac{R_4}{R_3 + R_4}\right)$$

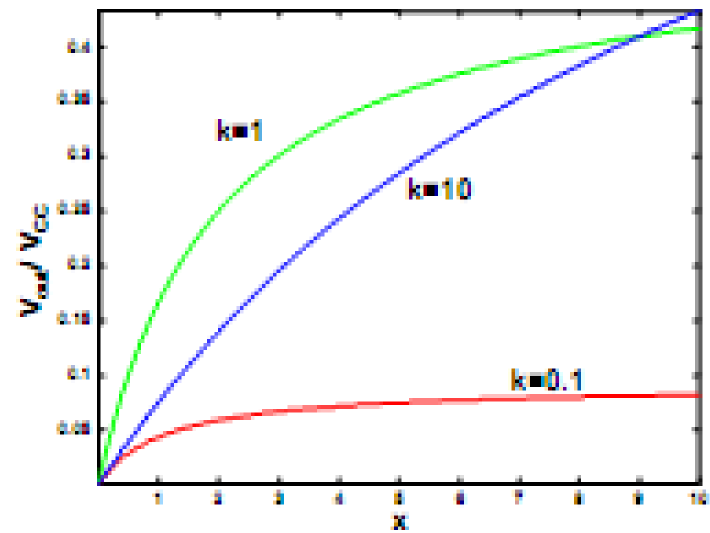
      - Advantage: speed



Wheatstone bridge

- **Assumptions**
  - Want to measure sensor fractional resistance changes $R_S = R_0(1+x)$
  - Bridge is operating near the balance condition:

$$k = \frac{R_1}{R_4} = \frac{R_2}{R_0}$$



- **The output voltage becomes**

$$V_{out} = V_{CC}\left(\frac{R_0(1+x)}{R_0k + R_0(1+x)} - \frac{R_4}{R_4k + R_4}\right) =$$

$$= V_{CC}\left(\frac{(1+x)}{k+(1+x)} - \frac{1}{k+1}\right) = V_{CC}\frac{kx}{(1+k)(1+k+x)}$$

- What is the sensitivity of the Wheatstone bridge?

$$S = \frac{dV_{out}}{dx} = V_{cc}\frac{d}{dx}\left(\frac{kx}{(1+k)(1+k+x)}\right) =$$

$$= V_{cc}\frac{k(1+k)(1+k+x) - kx(1+k)}{(1+k)^2(1+k+x)^2} =$$

$$= V_{cc}\frac{k}{(1+k+x)^2}$$

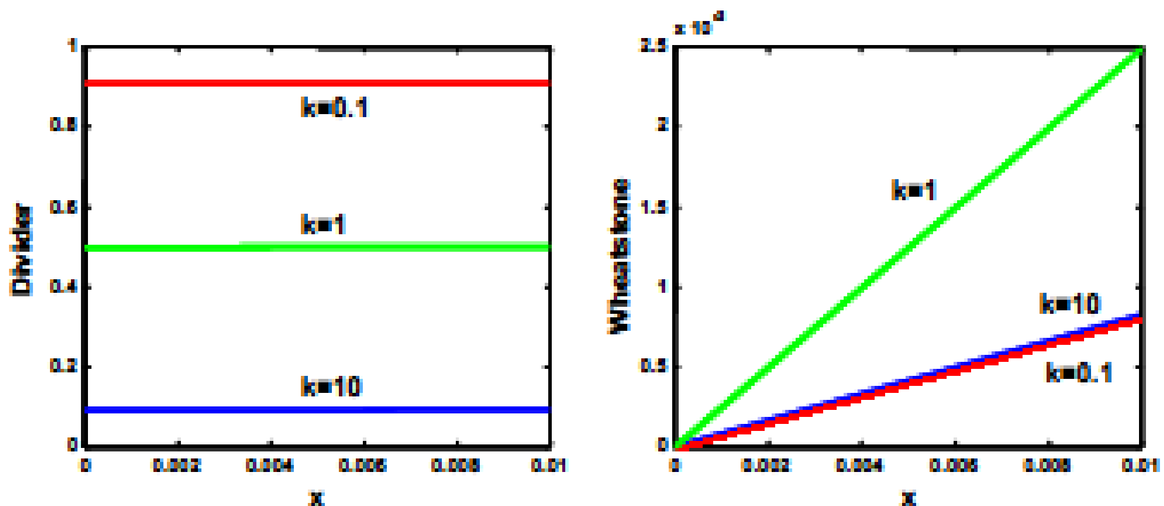
❑ The sensitivity of the Wheatstone bridge is the same as that of a voltage divider

- You can think of the Wheatstone bridge as a DC offset removal circuit

❑ So what are the advantages, if any, of the Wheatstone bridge?

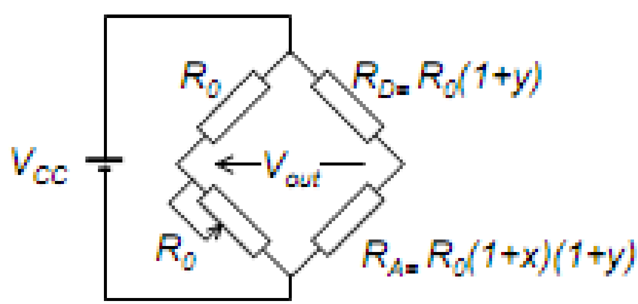
Voltage divider vs. Wheatstone for small x

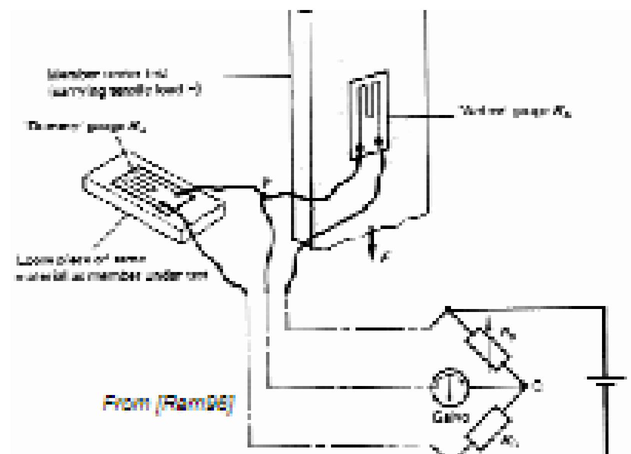
- The figures below show the output of both circuits for small fractional resistance changes
  - The voltage divider has a large DC offset compared to the voltage swing, which makes the curves look “flat” (zero sensitivity)
    - Imagine measuring the height of a person standing on top of a tall building by running a large tape measure from the street
- The sensitivity of both circuits is the same!
  - However, the Wheatstone bridge sensitivity can be boosted with a gain stage
    - Assuming that our DAQ hardware dynamic range is 0-5VDC, 0<x<0.01 and k=1, estimate the maximum gain that could be applied to each circuit



Compensation in a Wheatstone bridge

- Strain gauges are quite sensitive to temperature
  - A Wheatstone bridge and a dummy strain gauge may be used to compensate for this effect
    - The “active” gauge RA is subject to temperature (x) and strain (y) stimuli
    - The dummy gauge RD, placed near the “active” gauge, is only subject to temperature
  - The gauges are arranged according to the figures below
  - The effect of (1+y) on the right divider cancels out

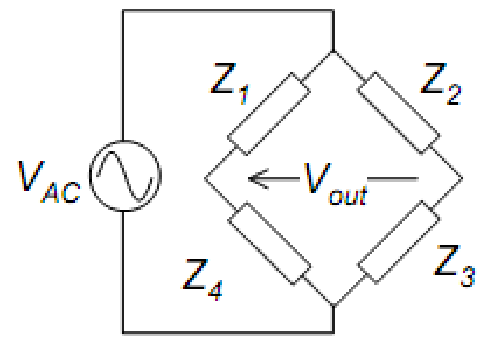




AC bridges

- **The structure of the Wheatstone bridge can be used to measure capacitive and inductive sensors**
  - Resistance replaced by generalized impedance
  - DC bridge excitation replaced by an AC source
- **The balance condition becomes**

$$\frac{Z_1}{Z_4} = \frac{Z_2}{Z_3}$$



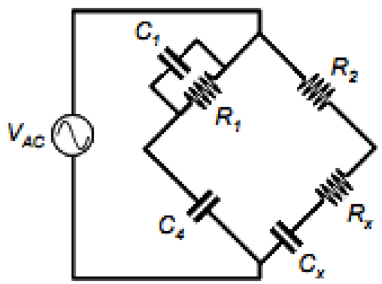
  - which yields two equalities, for real and imaginary components

$$R_1R_3 - X_1X_3 = R_2R_4 - X_2X_4$$
$$R_1X_3 + X_1R_3 = R_2X_4 + X_2R_4$$

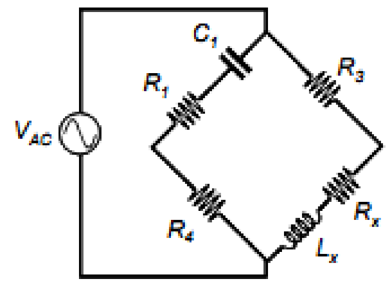
- **There is a large number of AC bridge arrangements**
  - These are named after their respective developer

AC Bridges

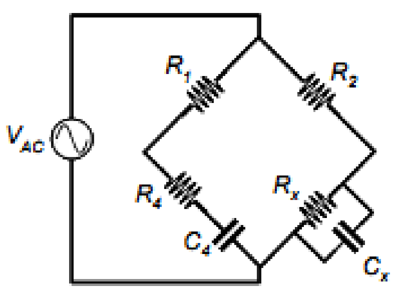
- **Capacitance measurement**
  - Schering bridge
  - Wien bridge
- **Inductance measurement**
  - Hay bridge
  - Owen bridge



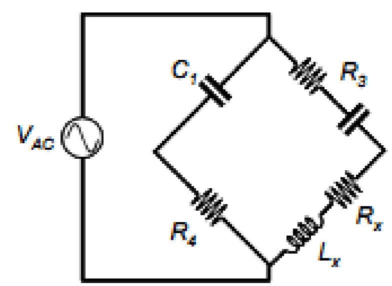
Schering



Hay



Wien



Owen

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

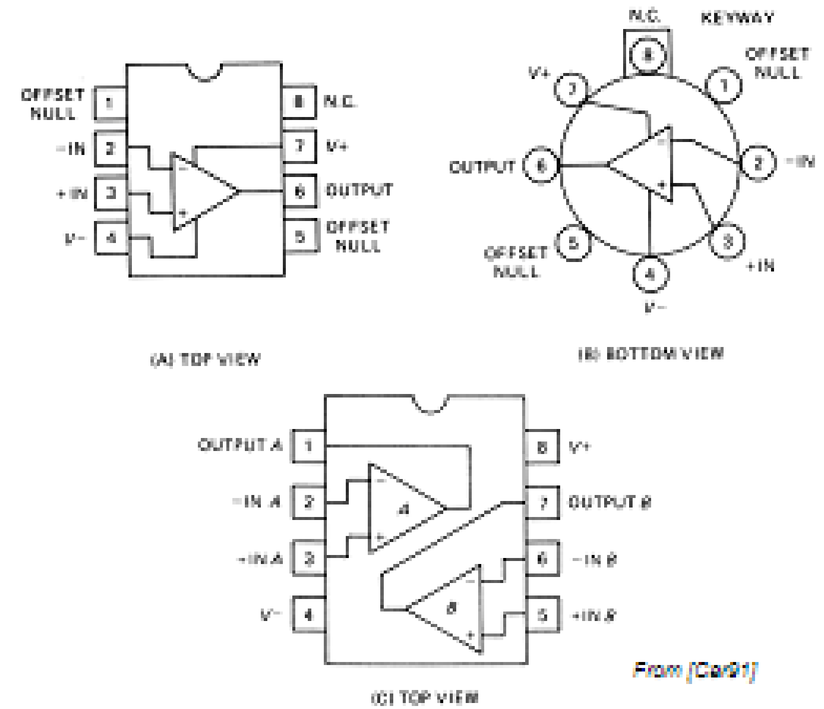


Fig. 12-6 Packaging for industry standard op-amp (741) in (A) DIP and (B) metal can packages, (C) dual op-amp such as 1458 device.

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

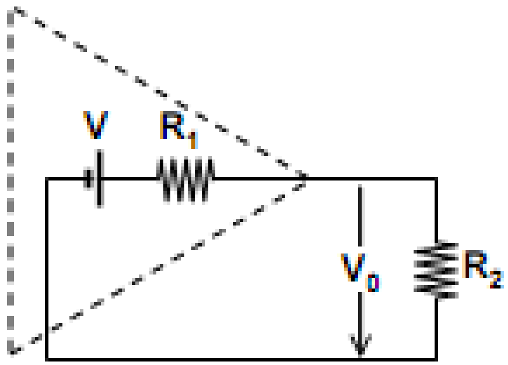
- Property No.1: Infinite Open-Loop Gain
  - Open-Loop Gain A_{vol} is the gain of the op-amp without positive or negative feedback
  - In the ideal op-amp A_{vol} is infinite
    - Typical values range from 20,000 to 200,000 in real devices
- Property No.2: Infinite Input Impedance
  - Input impedance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

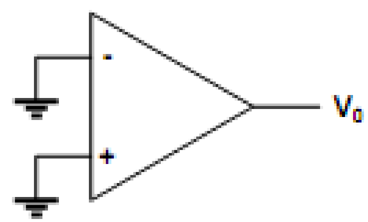
- Property No. 3: Zero Output Impedance
  - The ideal op-amp acts as a perfect internal voltage source with no internal resistance
    - This internal resistance is in series with the load, reducing the output voltage available to the load
    - Real op-amps have output-impedance in the 100-20Ω range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

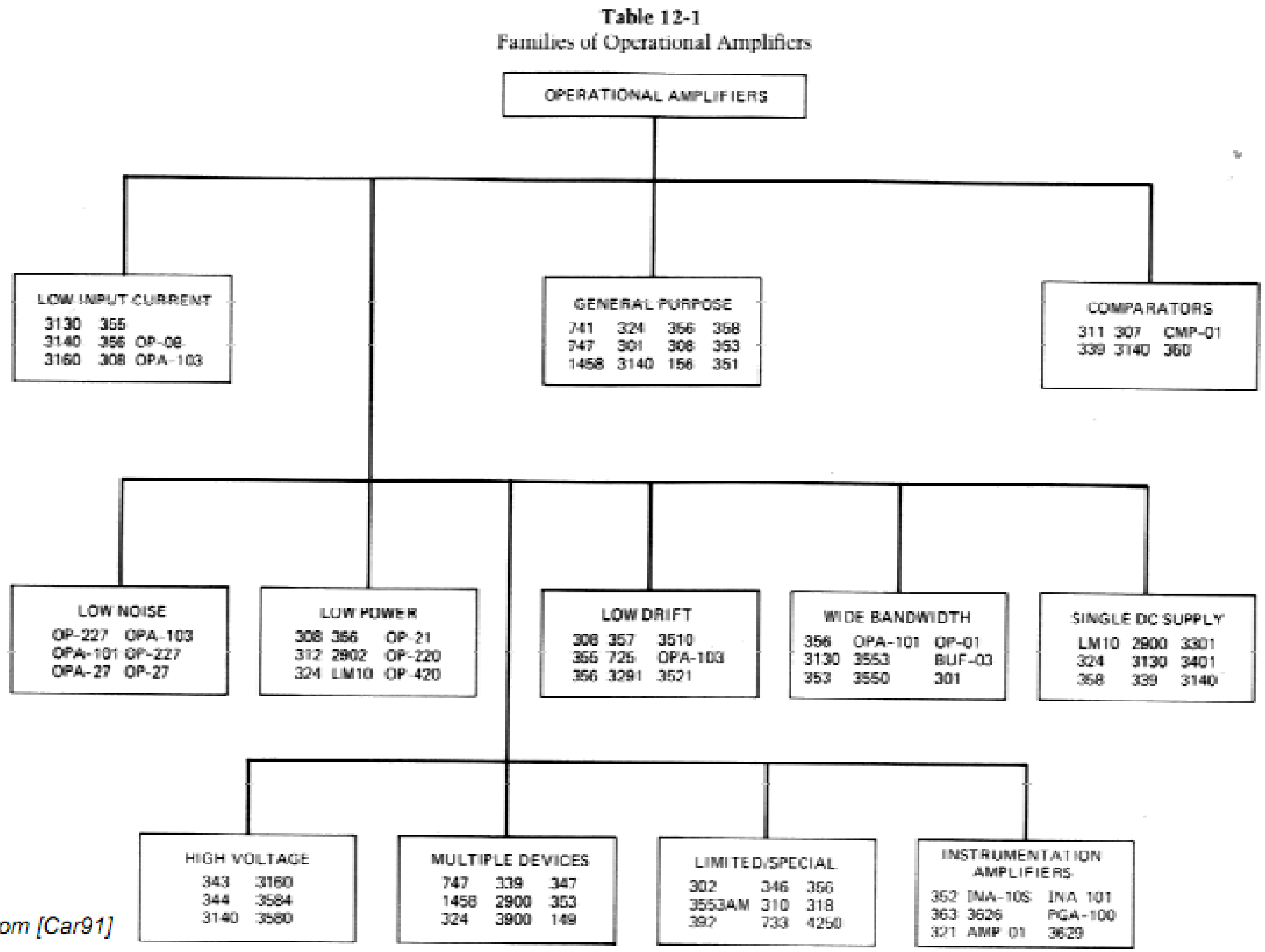
Operational amplifier types

- 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., ±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

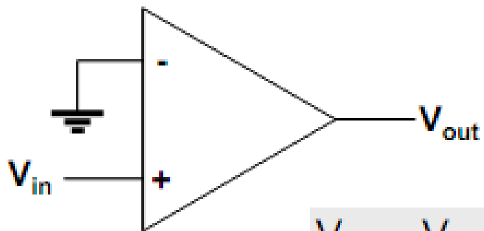
Families of operational amplifiers



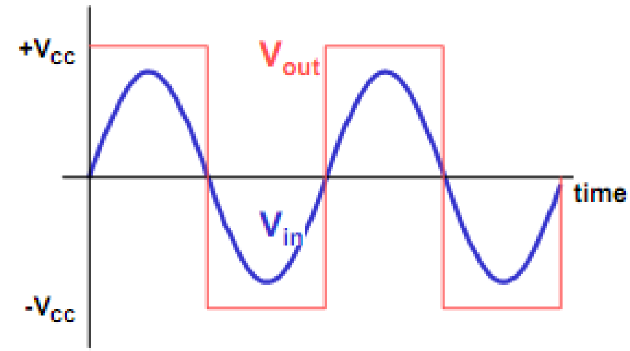
From [Car91]

Op-amp practical circuits

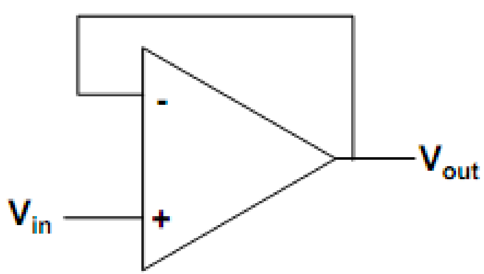
- **Voltage comparator**



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



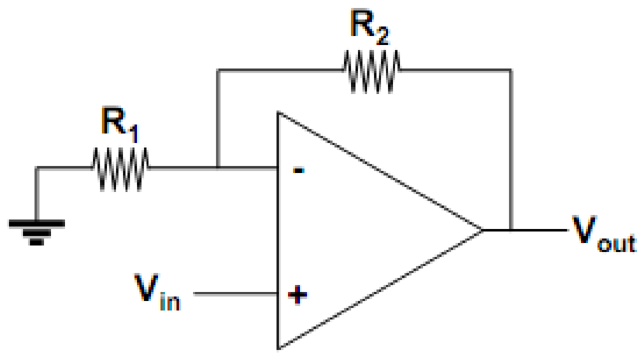
- **Voltage follower**
  - What is the main use of this circuit?
    - Buffering



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

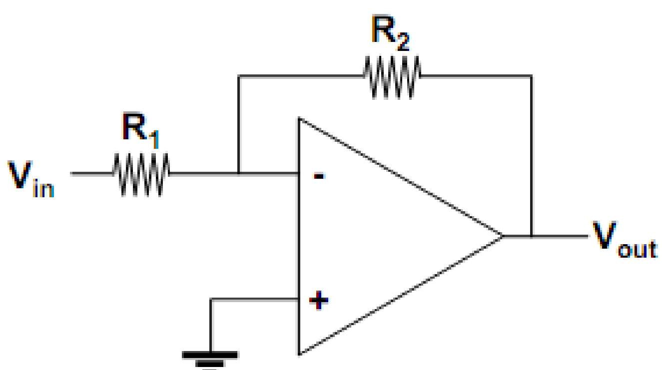
Inverting and non-inverting amplifiers

- Non-inverting amplifier



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

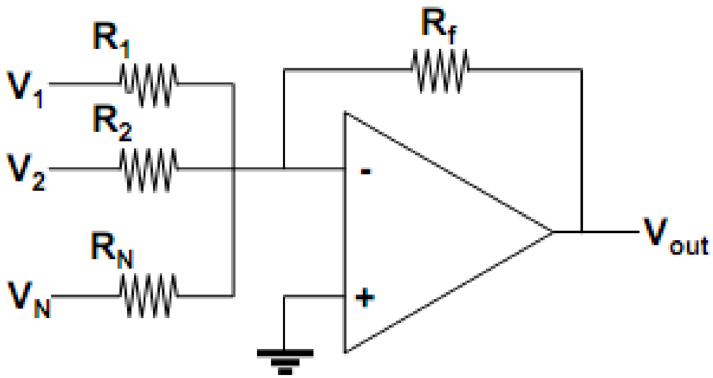
- Inverting amplifier



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

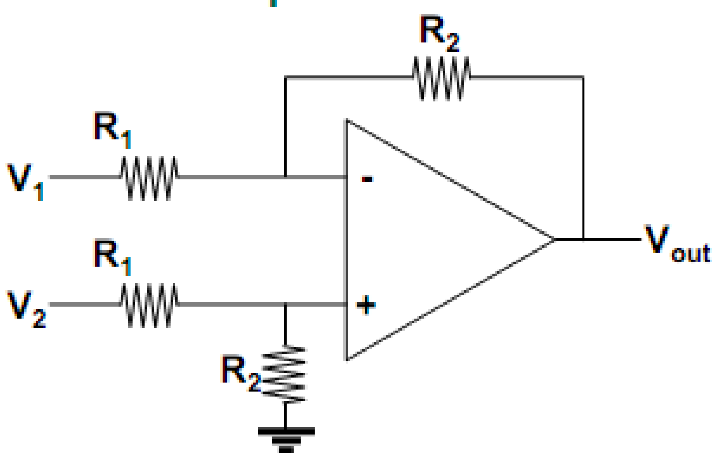
Summing and differential amplifier

- **Summing amplifier**



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

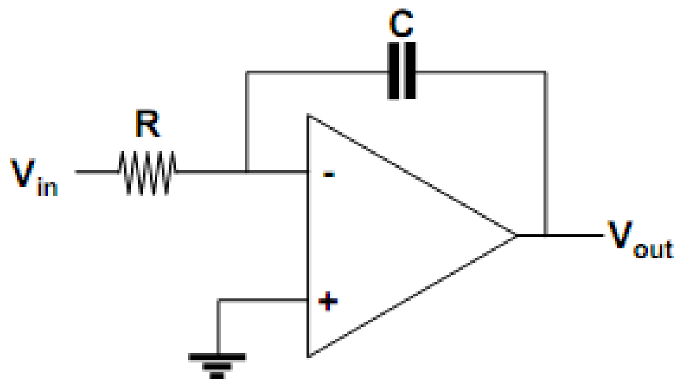
- **Differential amplifier**



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

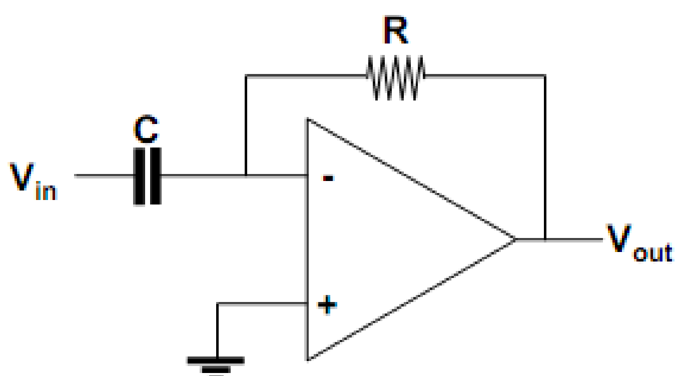
Integrating and differentiating amplifier

- **Integrating amplifier**



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

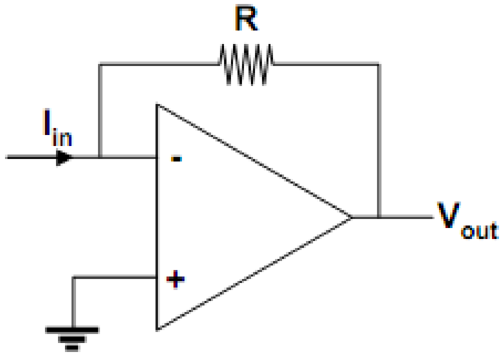
- **Differentiating amplifier**



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

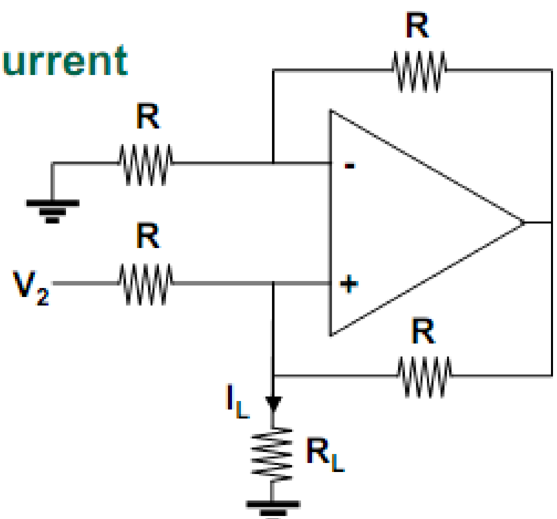
Current to voltage conversion

- Current-to-voltage



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

- Voltage to current



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

References

- [1] J. C. Whitaker, 1996, The Electronics Handbook, CRC Press
- [2] P. Elgar, 1998, Sensors for Measurement and Control, Addison Wesley Longman, Essex, UK.
- [3] R. Pallas-Areny and J. G. Webster, 1991, Sensors and Signal Conditioning, Wiley, New York