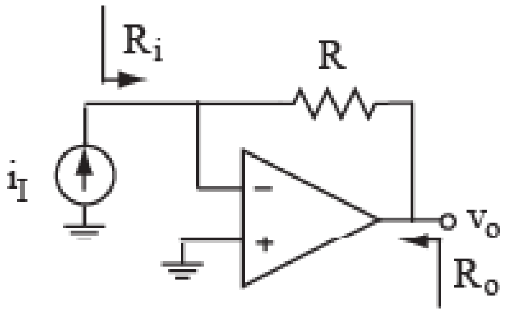
1) Op Amp fundamentals and ideal macro model

2) Circuits with resistive feedback

Circuits with resistive feedback

1) Current to voltage converters

(I – V) converter or trans-resistance amplifier; (v_o= A. i_I) , A (V/A); Sensitivity



$$v_o = \pm R \cdot i_I$$

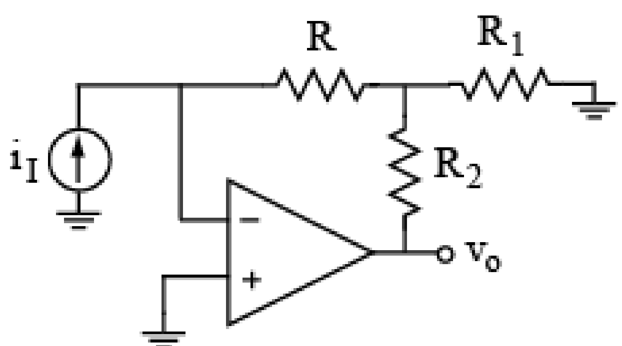
$R = Z(s) \longrightarrow$ Transimpedance Amplifier

$$R_i = 0$$

$$R_o = 0$$

Problem: R can be unrealistically large

Solution: High sensitivity (I – V) converter

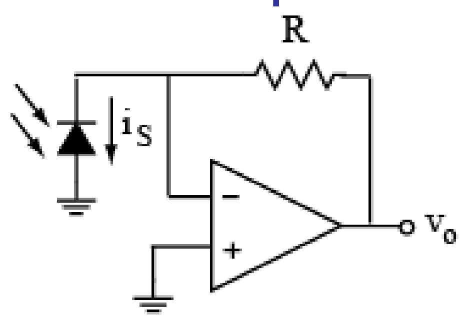


$$v_o = -\left(1 + \frac{R_2}{R_1} + \frac{R_2}{R}\right) \cdot R\, i_I$$

Circuits with resistive feedback

Photo Detector Amplifier: http://vorlon.case.edu/~flm/eecs245/Datasheets/Sharp%20photodevices.pdf

Photo detectors produce electric current in response to incident light



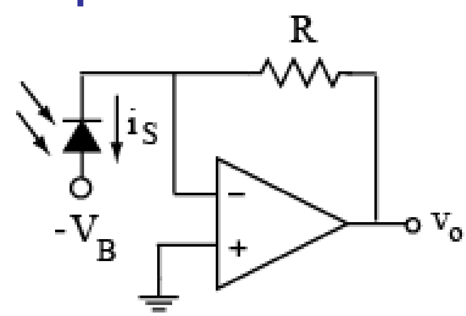
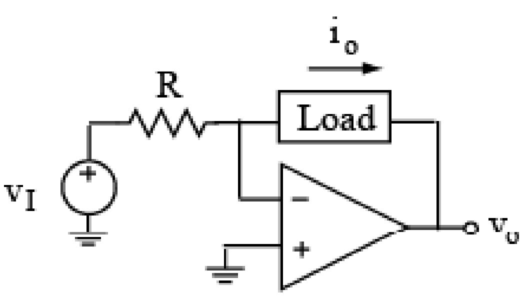


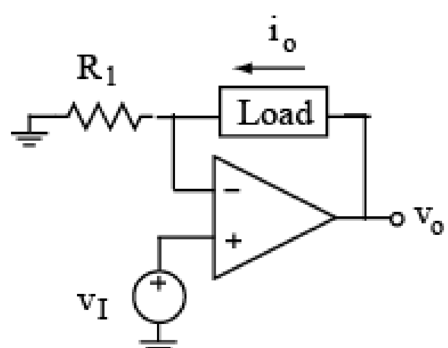
Photo Voltaic Mode (Zero Voltage) Lower noise, for instrumentation and measurement applications

Photo Conductivity Mode (Reserve Bias Voltage) Higher speed, for high frequency light beam modulation applications

2) Voltage to current converters

Floating Load(V – I) converter or trans-conductance amplifier; (i_o= A. v_I) , A (A/V); Sensitivity





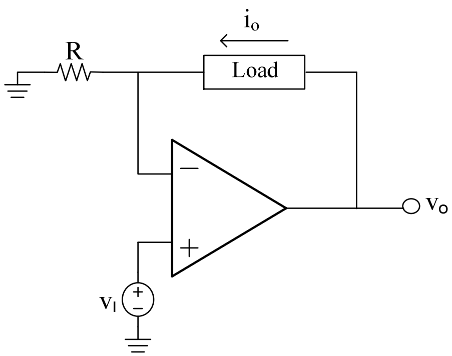
$$i_o = A\,v_I - \frac{v_L}{R_o}$$

R_o : Converter's output resistance

$R_o \rightarrow \infty$ (Ideal)

Circuits with resistive feedback

Practical Limitations

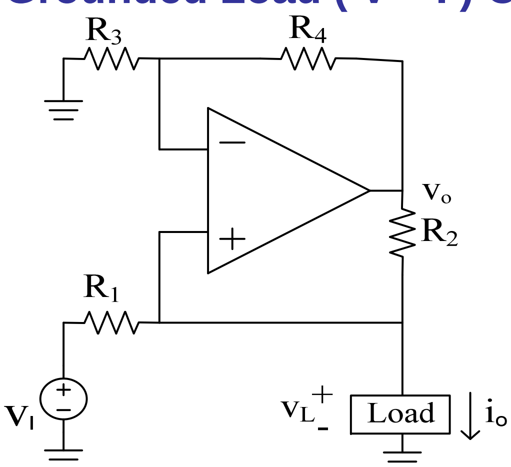


$$G_m = \frac{1}{R}\,\frac{a-(R/r_d)}{1+a+(r_o/R)+r_o/r_d}$$

$$R_o = (R \| r_d)(1+a)+r_o$$

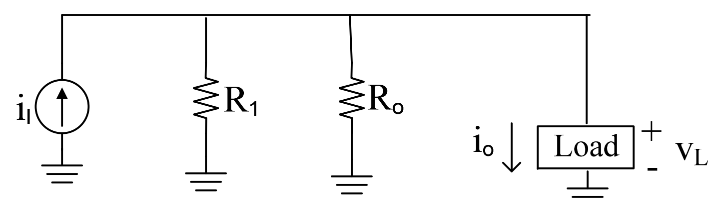
For a finite gain, a, the closed Loop gain exhibits errors and R_o is not infinite

Grounded Load (V – I) Converters (Howland Current Pump):



For $R_2/R_1 << R_4/R_3$

$$R_o \cong R_{eq} = -\frac{R_3 R_2}{R_4}$$



$$i_o = G_m v_I - \frac{v_L}{R_o}$$

$$R_o = \frac{R_2}{\frac{R_2}{R_1} - \frac{R_4}{R_3}}$$

For true current source behavior

$$\frac{R_2}{R_1} = \frac{R_4}{R_3} \qquad R_o \to \infty$$

Circuits with resistive feedback

Effects of Resistor Ratio Mismatch

Assume we want an ideal resistor match

$$\frac{R_4}{R_3} = \frac{R_2}{R_1}$$

In real implementations due to process variations the above equality become:

$$\frac{R_4(1+p)}{R_3(1-p)} = \frac{R_2(1-p)}{R_1(1+p)}$$

Where p is the percentage tolerance and the equality represents the worst case of matching, thus

$$\frac{R_4}{R_3} = \frac{(1-p)^2}{(1+p)^2}\frac{R_2}{R_1} \cong (1-p)^2(1-p)^2\frac{R_2}{R_1}$$

$$\frac{R_4}{R_3} \cong \left(1-4p+6p^2+\cdots\right)\frac{R_2}{R_1}$$

Circuits with resistive feedback

Neglecting Higher-Order Terms:

$$\frac{R_4}{R_3} \cong (1-4p)\frac{R_2}{R_1}$$

$$\frac{R_4}{R_3} = \frac{R_2}{R_1}\left(1-|\varepsilon_{max}|\right) \quad ; \quad \varepsilon_{max} \cong 4p$$

For example for 5% resistance variation we have

$|\varepsilon_{max}| \cong 4 \times 0.05 = 0.2$ which means a 20% mismatch

Thus for the Howland Current Pump

$$R_o \cong \left.\frac{R_1}{\varepsilon}\right|_{R_1=20K} = \frac{20\times 10^3}{2\times 10^{-1}} = 100K\Omega$$

Now assume we want $|R_o|_{min} = 100M\Omega$, thus it is required that $|\varepsilon_{max}| = 20K/10^8 = 2\times 10^{-4}$ then

$$p \le \frac{|\varepsilon_{max}|}{4} = 0.5\times 10^{-4}\% \text{ which implies almost ideal accuracy for resistors}$$

Circuits with resistive feedback

3) Current Amplifiers

(I – I) converter or current amplifier; (i_o= A. i_I) , A (A/A); Sensitivity

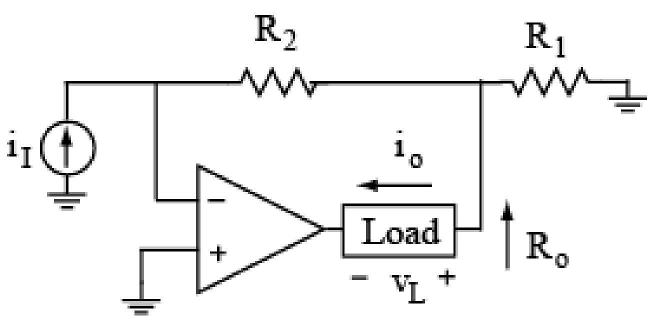
Applications: Two-wire remote sensing instrumentation
Photo-detector output conditioning.

$$i_o = A\, i_I - \frac{v_L}{R_o}$$

R_o : Converter's output resistance

$R_o \rightarrow \infty$ (Ideal)

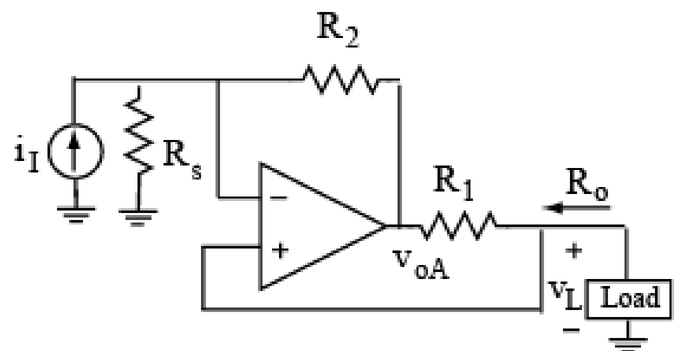
Floating Load



$$i_o = i_I\left(1 + \frac{R_2}{R_1}\right)$$

$$R_o \rightarrow \infty$$

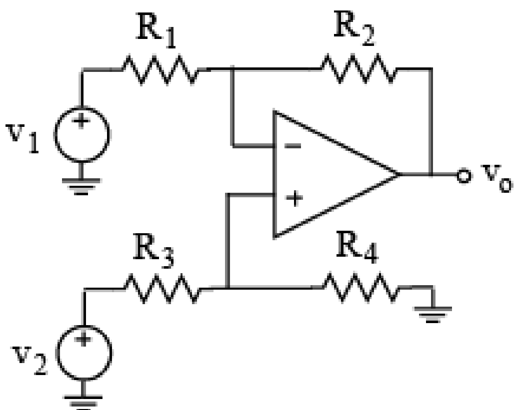
Grounded Load



$$i_o = \left(-\frac{R_2}{R_1}\right) i_I + \left(\frac{R_2}{R_1 R_s}\right) v_L$$

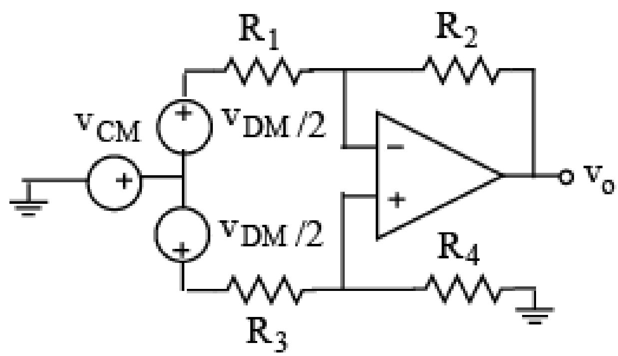
Circuits with resistive feedback

4) Difference Amplifiers



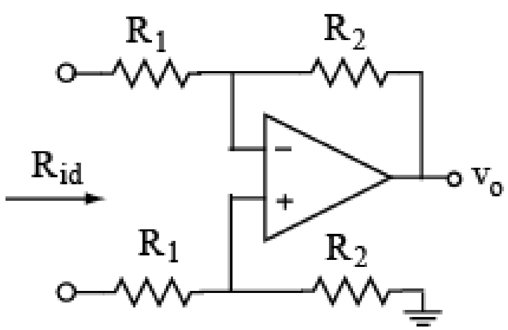
$$\frac{R_1}{R_2} = \frac{R_3}{R_4} \rightarrow v_o = \left(\frac{R_2}{R_1}\right) . [v_2 - v_1]$$

Introducing differential and common mode signals

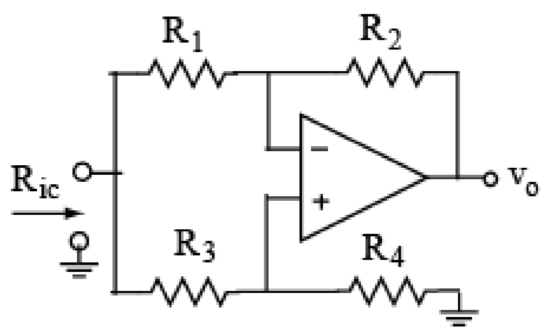


$$v_{DM} = v_2 - v_1$$
$$v_{CM} = (v_2 + v_1) / 2$$

In practice, extracting a small differential signal from a high common mode environment
And amplifying that signal is a challenging task



$$R_{id} = 2\,R_1$$



$$R_{ic} = (R_1 + R_2) / 2$$

Circuits with resistive feedback

Effect of Resistance Mismatches:

The difference amplifier is insensitive to v_{CM} only if the op-amp is ideal and the bridge Is balanced.

Unbalanced Bridge:

$$\frac{R_4}{R_3} = \frac{R_2}{R_1}(1 - \varepsilon)$$

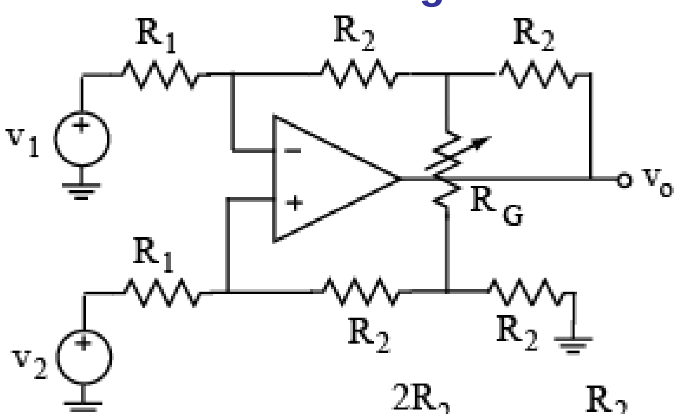
$$v_o = \underbrace{\left(\frac{R_2}{R_1}\right)\left[1 - \frac{R_1 + 2R_2}{R_1 + R_2}.(\varepsilon / 2)\right]}_{A_{DM}} v_{DM} + \left[\underbrace{\frac{R_2 . \varepsilon}{R_1 + R_2}}_{A_{CM}}\right] v_{CM}$$

$$CMRR = 20 \log | A_{DM} / A_{CM} |$$

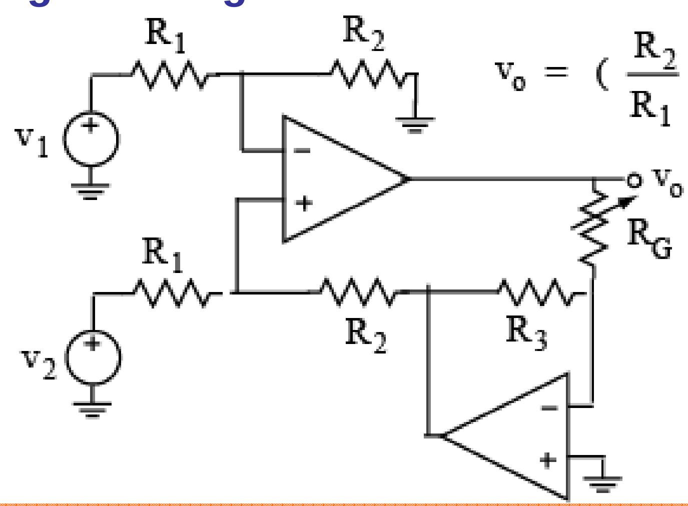
CMRR is a figure of merit. In ideal case: $A_{CM} \longrightarrow 0$, $CMRR \longrightarrow \infty$

<u>Variable gain and linear variable gain difference amplifiers</u>

To have a variable gain without disturbing the bridge balance:



$$v_o = \left(\frac{2R_2}{R_1}\right)\left(1 + \frac{R_2}{R_G}\right)[v_2 - v_1]$$



$$v_o = \left(\frac{R_2}{R_1}\frac{R_G}{R_3}\right)[v_2 - v_1]$$

Circuits with resistive feedback

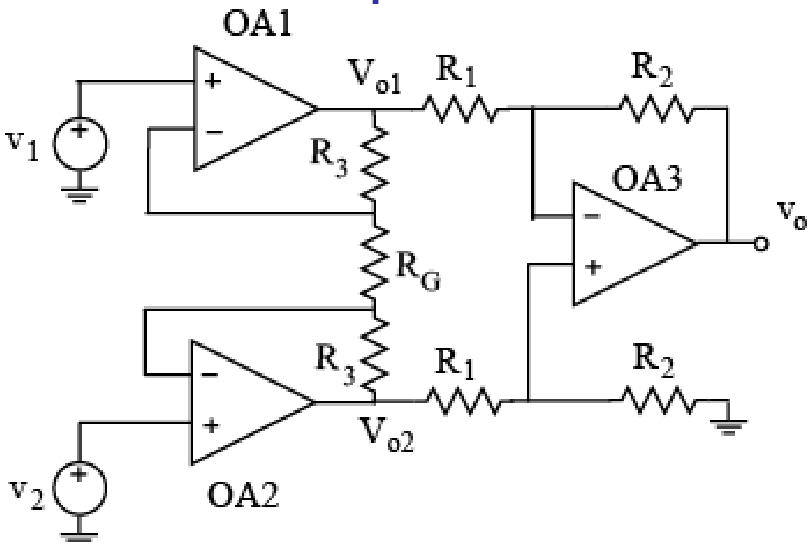
5) Instrumentation Amplifiers

IA is a difference amplifier with:
(a) Extremely high CM and DM impedances
(b) Very low output impedance
(c) Extremely High CMRR

Example : Transducer output in process control and biomedicine

Triple – Op amp IAs:

To achieve high CM and DM impedances, we use two buffers at the input of the a difference amplifier:



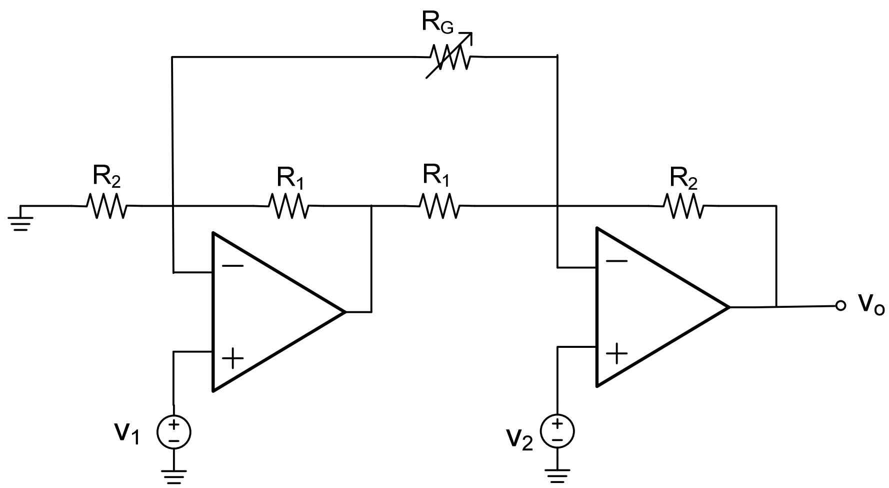
$$v_o = \left(\frac{R_2}{R_1}\right)\left(1 + \frac{2R_3}{R_G}\right)[v_2 - v_1]$$

- **OA1, OA2 are non-inverting amplifiers (infinite input impedance)**
- **OA3 has a zero output impedance**
- **By varying R_G we can avoid perturbing the bridge balance**

Example: AD 522 or 1N 101

Circuits with resistive feedback

Dual – Op amp IAs:



$$v_o = (1 + \frac{R_2}{R_1})[v_2 - v_1]$$

$$v_o = (1 + \frac{R_2}{R_1} + \frac{2R_2}{R_G})[v_2 - v_1]$$

- High Ri and low Ro
- High CMRR

Example: OP 227

<u>Drawback:</u> The inputs are treated asymmetrically and v_1 has additional delay; so the common mode components of the two signals do not cancel each other.

Monolithic IAs:

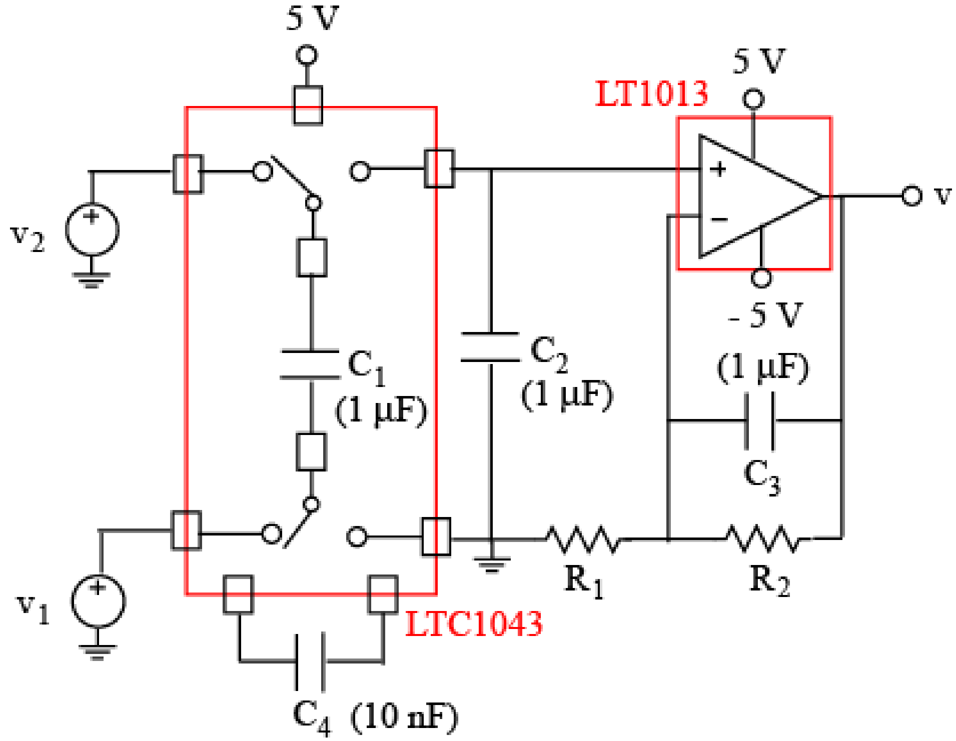
Special IAs for instrumentation, better optimization of CMRR, gain, linearity, noise

Examples: Amp 01, AMP 05 (analog devices)

Circuits with resistive feedback

Flying Capacitor Techniques:

Very high CMRR



1) Switching to Left : Charging C_1 to $v_1 - v_2$
2) Flipping to right : Transferring Charge from C_1 to C_2
3) Continuous Clocking ; $V_{C1} = V_{C2}$ (Equilibrium)
4) $v_o = (1 + (R_1/R_2))(v_1 - v_2)$

LTC1043 has an on chip clock generator
To operate the switches at a frequency set
By C_4

This circuit completely ignores common
-mode signals (CMRR ~ 120 dB)

Circuits with resistive feedback

6) <u>Transducer Bridge Amplifier:</u>

Resistive transducer: Resistance varies as a consequence of some environmental Condition such as:

- **Temperature : Thermostats, Resistance temperature detectors (RTDs)**
- **Light : Photo-resistors**
- **Strain, Pressure: Strain gauges, piezoelectric transducers**

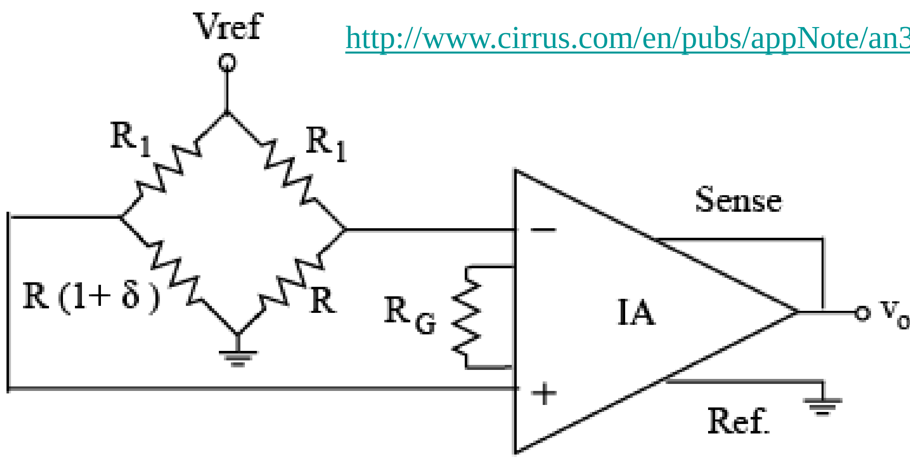
Transducer resistance deviation: R + ΔR
R: Reference condition; ΔR: Deviation; δ = (ΔR)/R: Fractional deviation

Transducer Bridge

$$v_o = A\,V_{ref}\,\frac{\delta}{1+\frac{R_1}{R}+\left(1+\frac{R}{R_1}\right)(1+\delta)}$$

$$\delta \ll 1,\ R_1 = R \longrightarrow v_o = A\,V_{ref}\,\frac{\delta}{4}$$

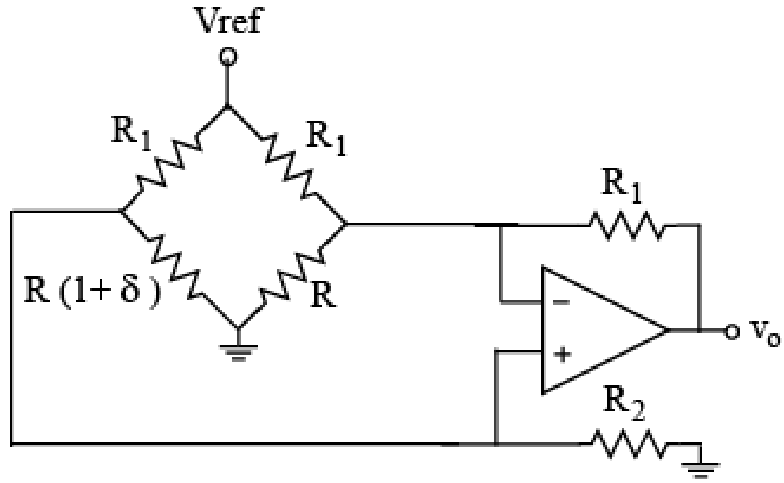
http://www.cirrus.com/en/pubs/appNote/an31.pdf



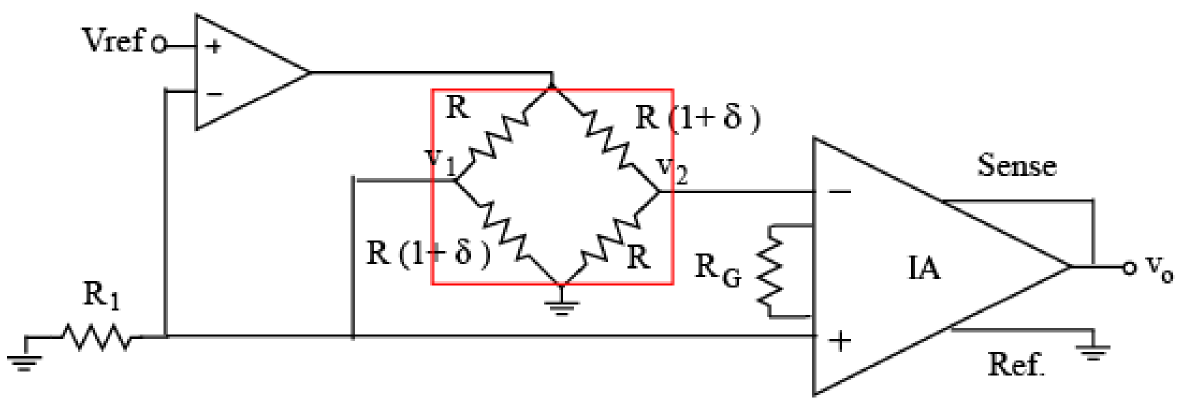
Circuits with resistive feedback

Single op amp amplifier

$$v_o = A\,V_{ref}\,\frac{\delta}{\frac{R_1}{R} + (1 + \frac{R_1}{R_2})(1+\delta)}$$



Bridge Linearization:



Linearization by driving bridge With a constant current.

$$v_o = \frac{A\,.\,R\,.V_{ref}}{2R_1}\,\delta$$