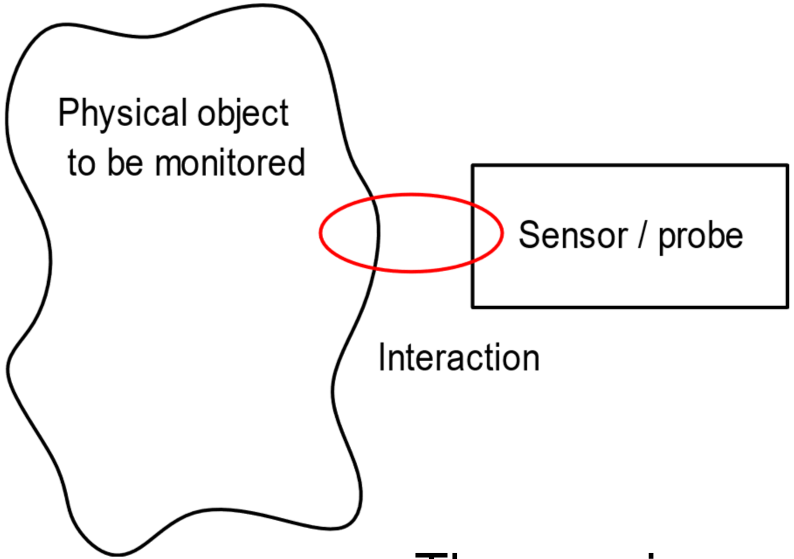
Sensor / object electrical coupling



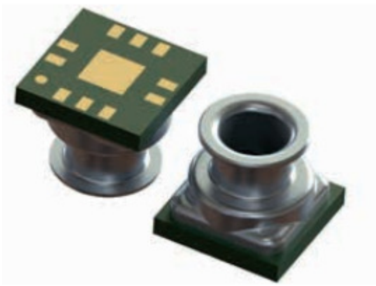
The physical object is a solid, liquid or gaseous to which the quantity to be measured belongs
It can be a very simple object (e.g. a single-piece mechanical part) or a complex object, like the human body or a chemical reactor

The sensing operation requires the sensor / probe to interact with the physical object.
The sensor package (housing) must be designed to enable the required interaction and, at the same time, protect the sensors

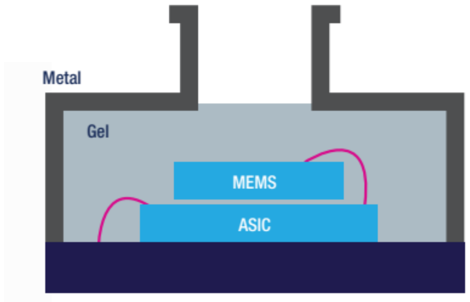
Sensor - object interaction

- The interaction can be contactless (e.g. IR thermometer) or with contact (e.g. a thermocouple temperature probe).
- Protection of the sensing elements is particularly important, for example, when the physical object is in liquid phase (liquid flow sensors, ion concentration sensors) or it is a corrosive gas.

Example: a liquid pressure sensor (10-bar resistant, usable for depth meters)



LPS33HW



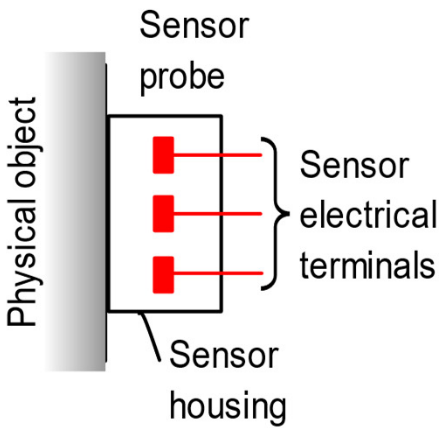
Insulating gel:

1) Avoid direct contact with the liquid but ….

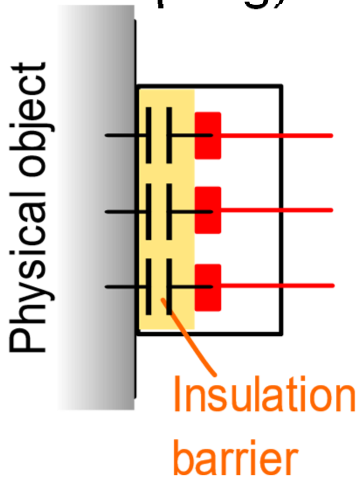
2) Transmit pressure from the liquid to the MEMS chip

Electrical connection and continuity

- A particular aspect that have to be assessed is the degree of electrical contact between the sensor terminals and the physical object



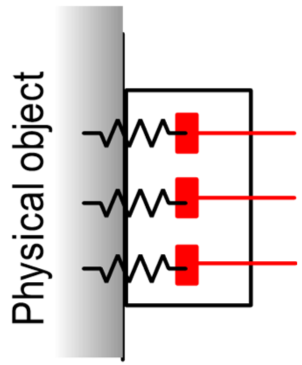
Only capacitive coupling (AC coupling)



C: order of pF

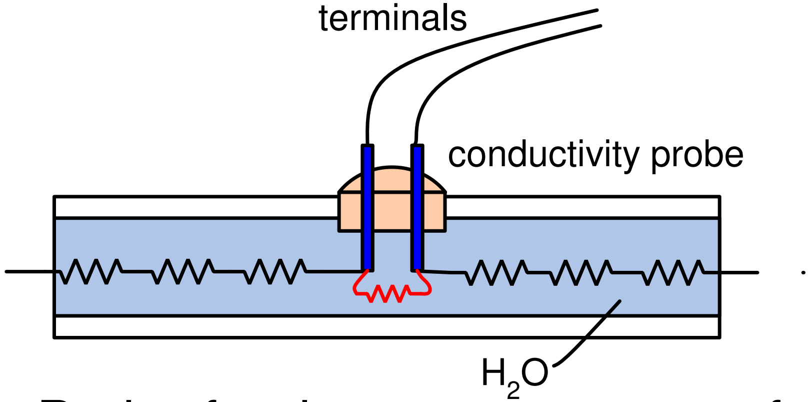
V_{ISO} (maximum that the barrier can withstand)

Only resistive coupling



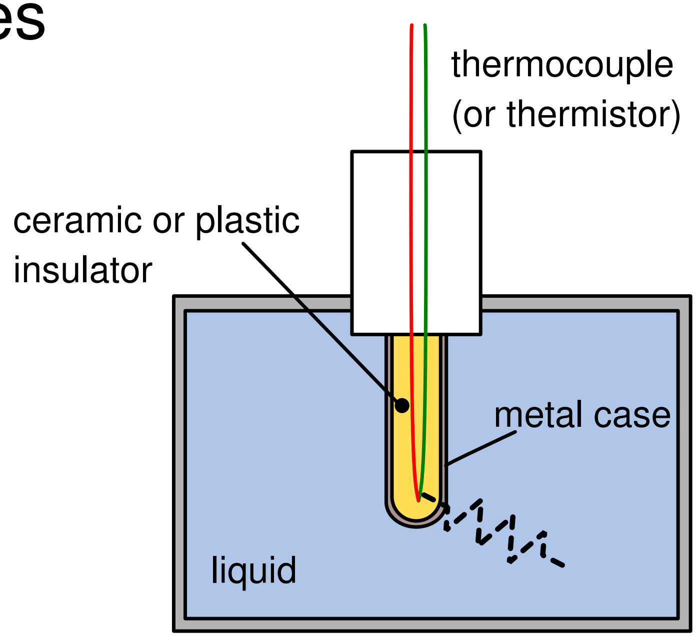
The presence of a dc path can be unwanted (defective insulation) or necessary

Examples



Probe for the measurement of the water conductivity (used to monitor the quality of water supplies)

In this case, electrical continuity is necessary to perform the measurement



Temperature probe

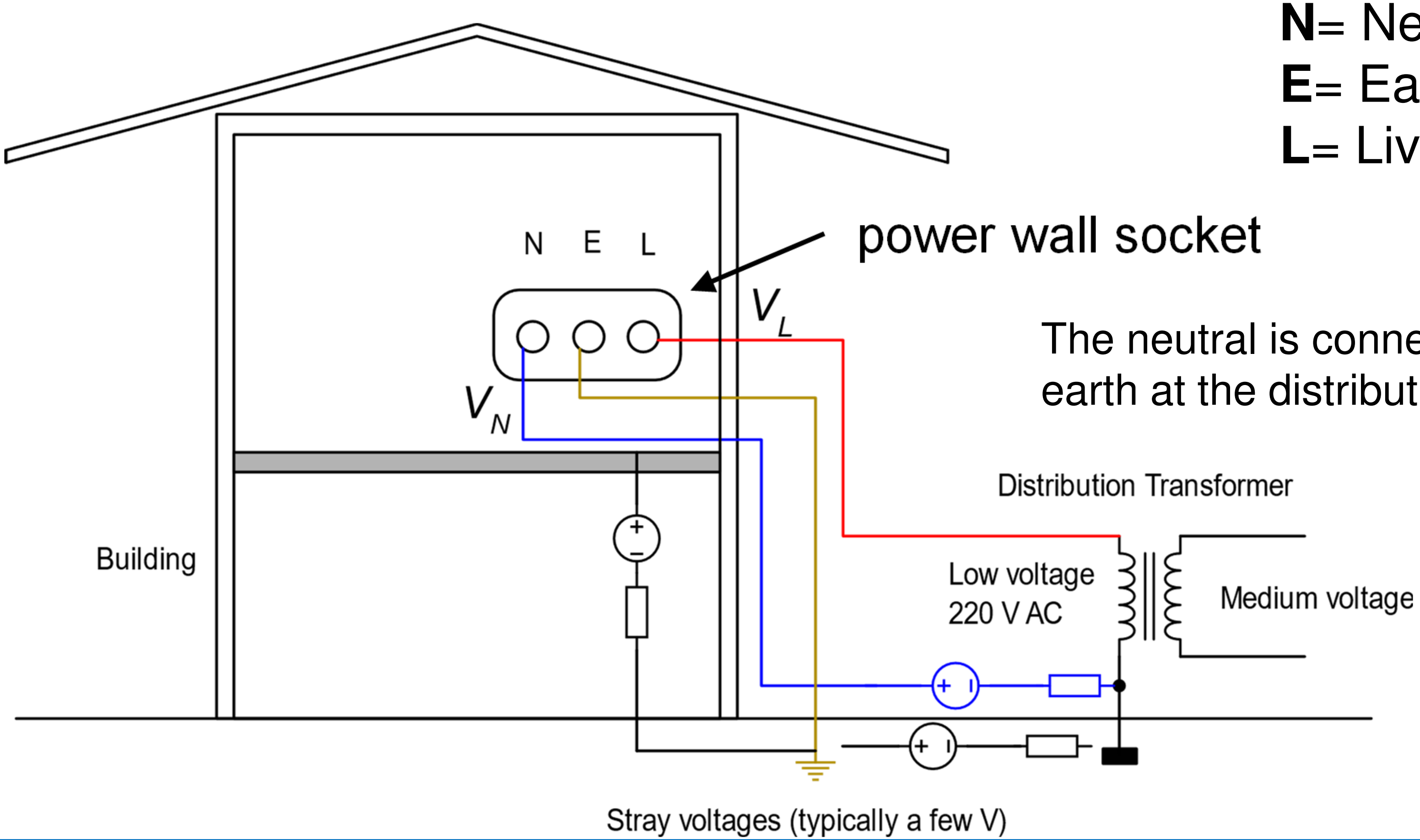
Electrical continuity is not necessary, but a leakage conductance between the sensor terminal and the liquid can develop when the insultaor properties degrade with time

Voltages due to mains inside a building

N= Neutral
E= Earth
L= Live (or "phase")

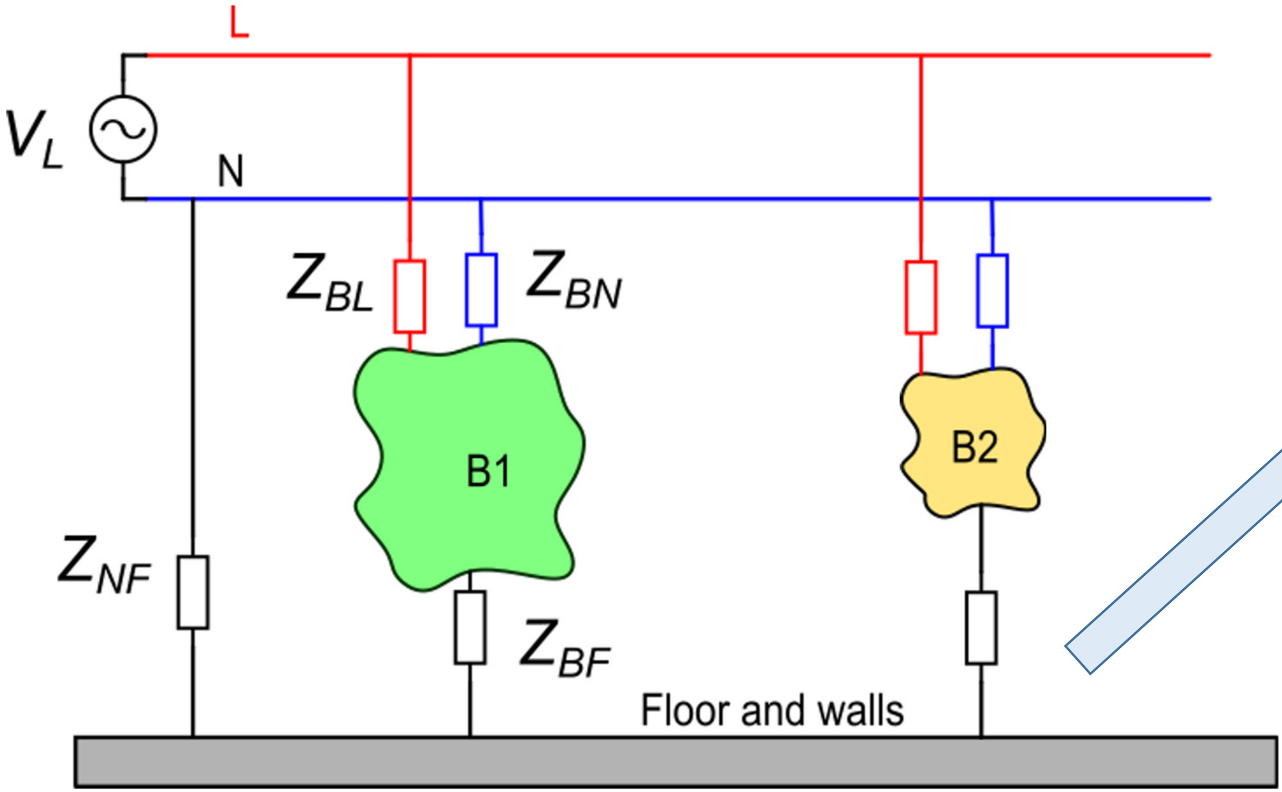
power wall socket

The neutral is connected to the earth at the distribution transformer

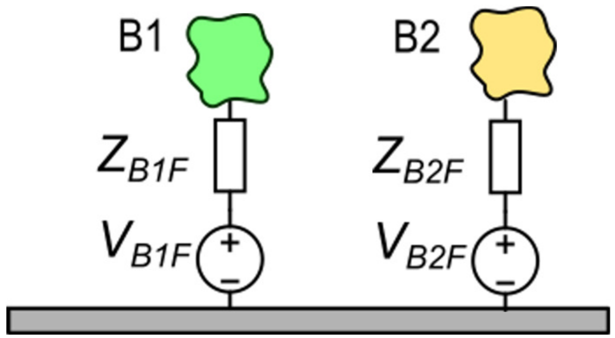


Consequences of the presence of AC power distribution

B1: conducting body



$$Z_{NF} \approx 0$$

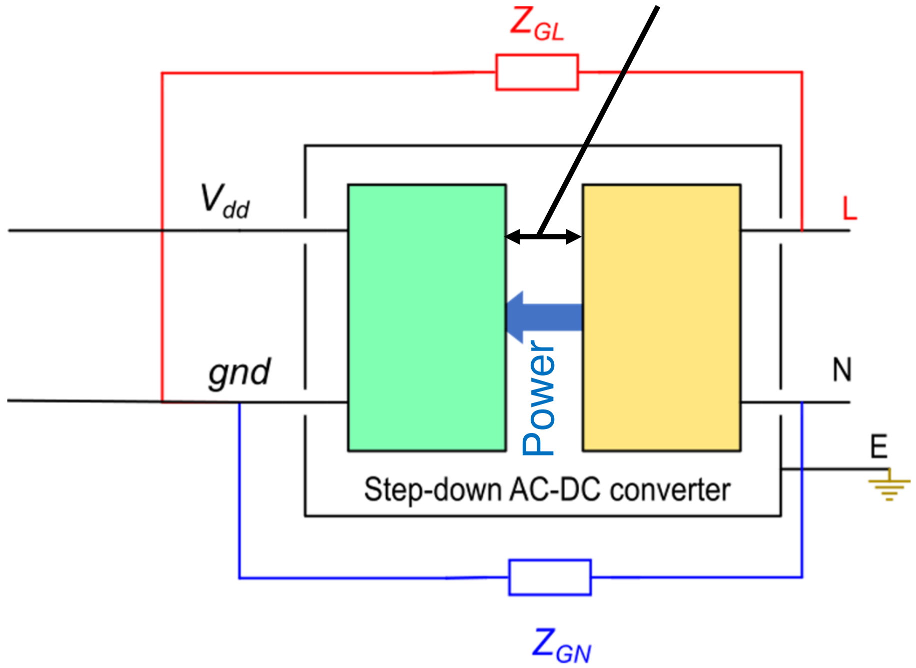


$$V_{B1F} = \frac{Z_{BF} \parallel Z_{BN}}{Z_{BF} \parallel Z_{BN} + Z_{BL}} V_L$$

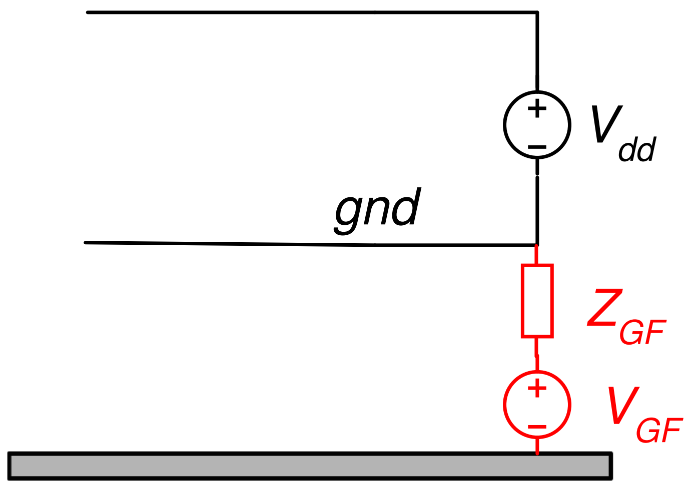
$$Z_{B1F} = Z_{BF} \parallel Z_{BN} \parallel Z_{BF}$$

Generally: $V_{B1F} \neq V_{B2F}$

Particular case: the power supply



In any power supply it is impossible to avoid leakage impedances (Z_{GL}, Z_{GN}) between the input output terminals



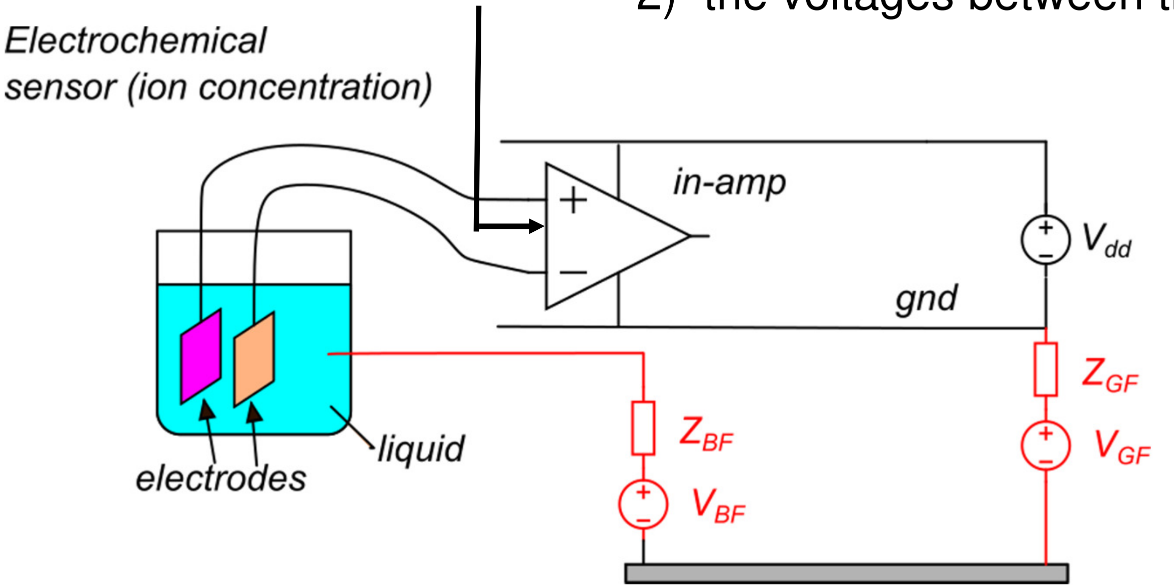
This is the actual equivalent circuit that takes into account also the connection towards the floor and the relative voltage.

A few significant cases

- Presence of electrical continuity between a conductive physical object and the sensor terminals.

Example

Suppose that: 1) the input impedance is infinite
2) the voltages between the electrodes and the liquid are negligible



With this simplified model, the input common mode voltage of the in-amp is:

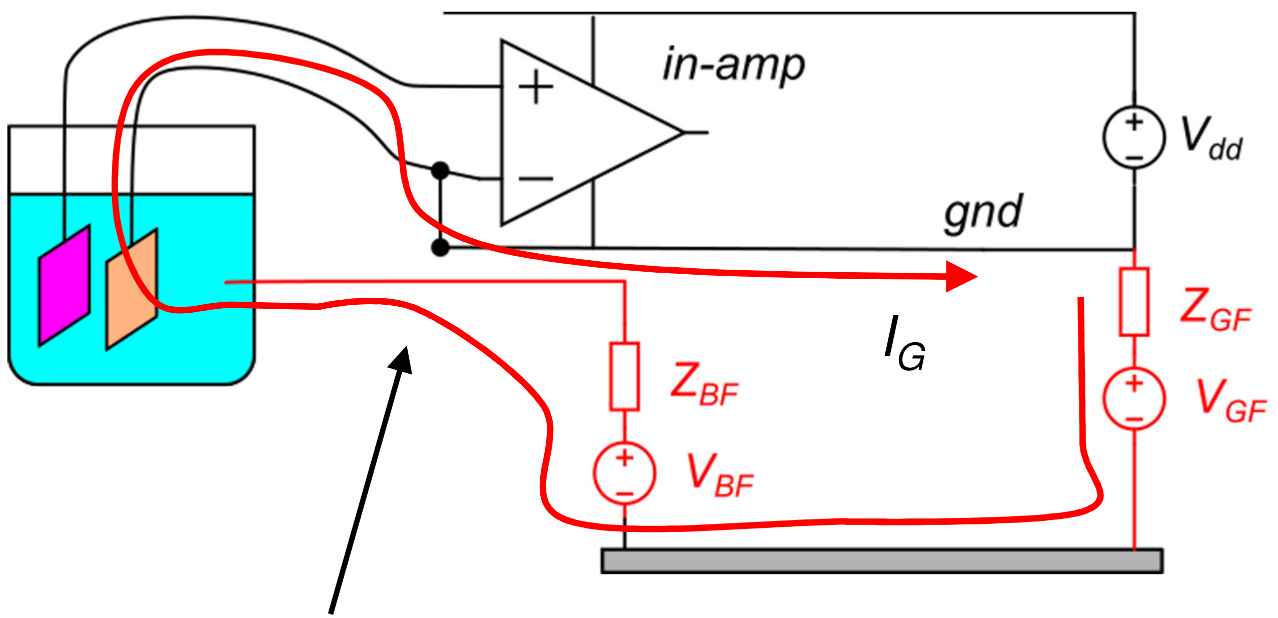
$$V_C \cong V_{BF} - V_{GF}$$

Since V_{BF} and V_{GF} are important fraction of the mains voltage (220 V r.m.s):

➡ The amplifier will be damaged or the protection at the input terminals activate, making the measurement meaningless

Two possible solutions:

1. Connect one of the two terminals to gnd. In this way, the input common mode voltage is close to zero.

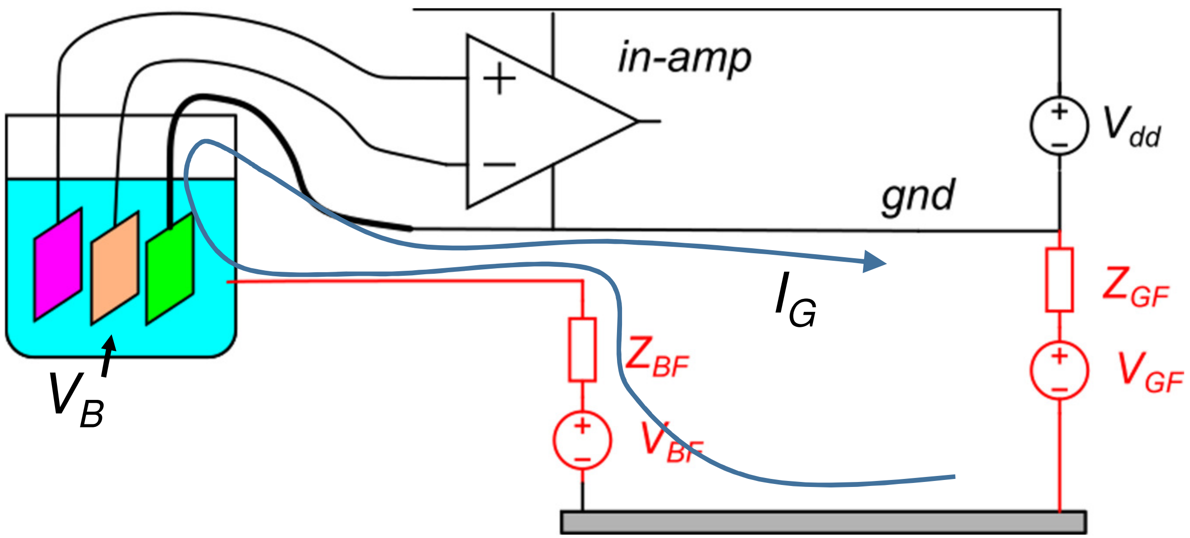


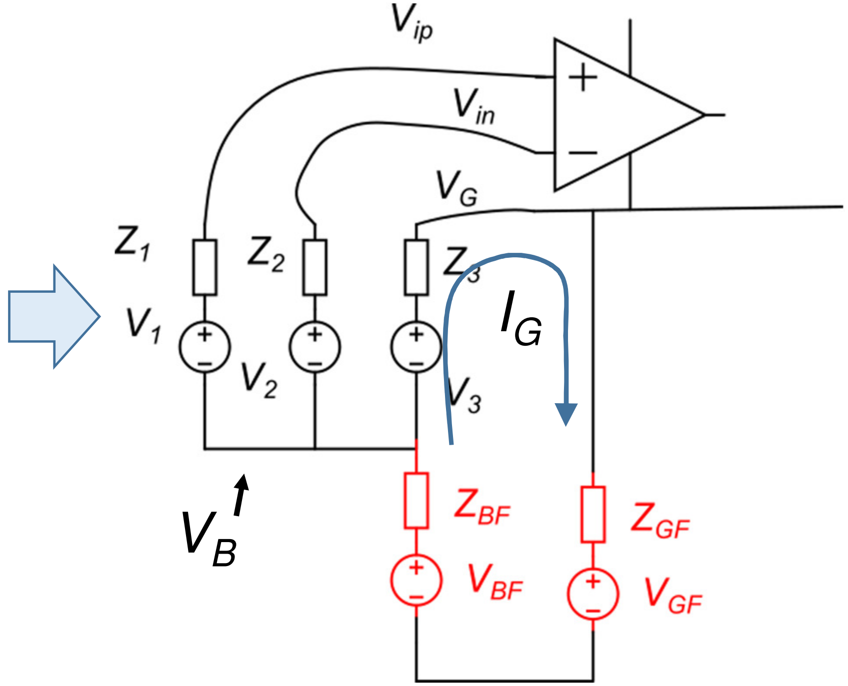
connection of one input to gnd

The problem with solution is that a current flows trough one of electrodes. Since the series resistance between the electrode and the solution can be relatively high, the current can cause an important error in the measurement.

Second solution

2. Use a third electrode to connect the gnd of the amplifier to the fluid ("Three electrode measurement")

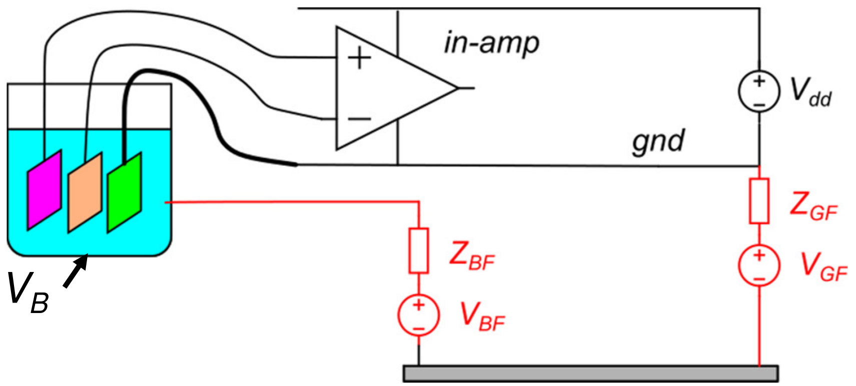


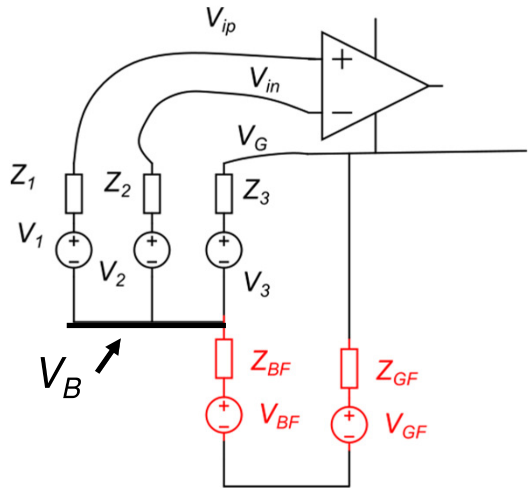


$$V_B - V_G = Z_3 I_G - V_3$$

$$V_C = \frac{(V_{ip} - V_G) + (V_{in} - V_G)}{2} = \frac{(V_1 + V_B) + (V_2 + V_B) - 2V_G}{2} = \frac{(V_1 + V_2)}{2} + V_B - V_G$$

Second solution





Such a small V_C can be tolerated by the amplifier

If the input amplifier impedance is >> Z_1, Z_2:

$$V_C = \frac{(V_1 + V_2)}{2} + V_B \qquad V_B = Z_3 I_G - V_3$$

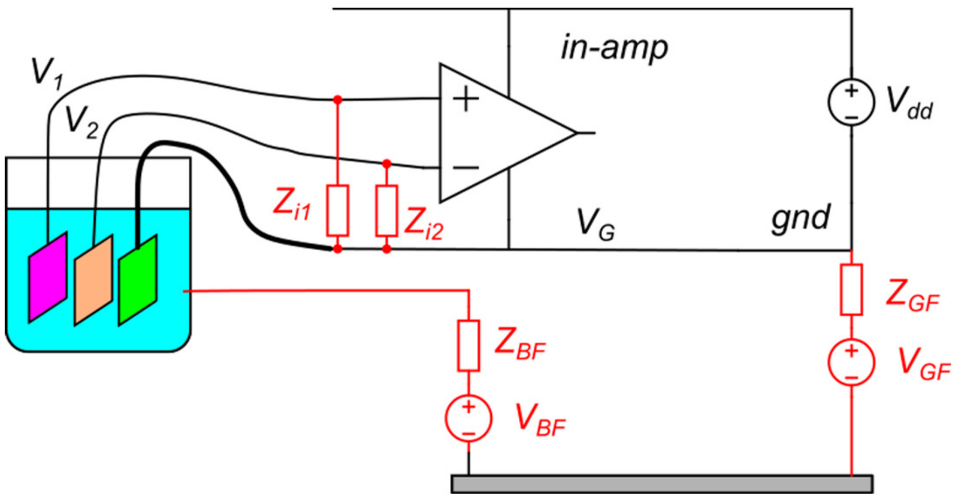
$$V_{id} = V_{ip} - V_{in} = V_1 - V_2$$

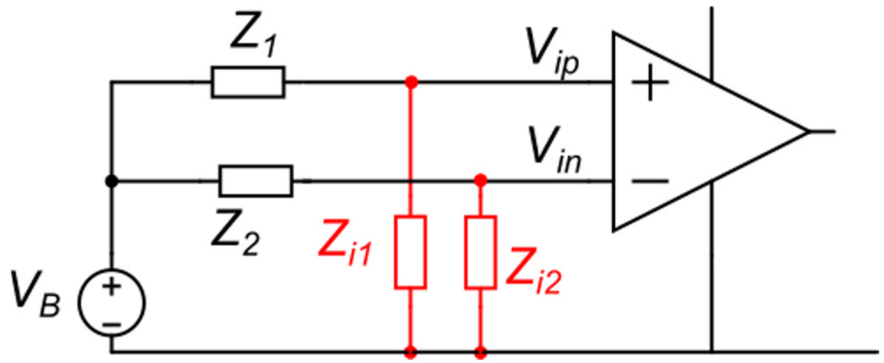
$$Z_3 I_G = \frac{V_{BF} - V_{GF} + V_3}{Z_{BF} + Z_{GF}} Z_3$$

If $Z_3 << Z_{BF}+Z_{GF}$, the effect of voltages V_{BF} and V_{GF} on V_C can be as small as a **few hundred mv**

The differential voltage is not affected by V_{BF} and V_{GF}

Effect of the finite input impedances of the amplifier



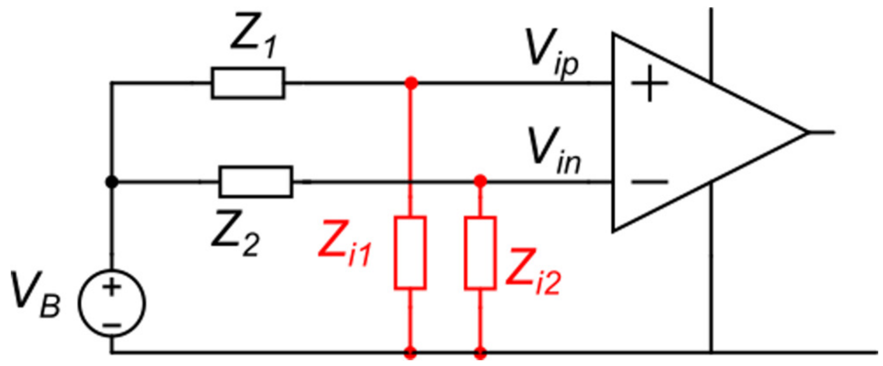


$$V_B = Z_3 I_G - V_3 \cong Z_3 I_G$$ (this is an AC disturbance voltage)

$$V_{id} = V_{ip} - V_{in} = \frac{Z_{i1}}{Z_{i1}+Z_1} V_B - \frac{Z_{i2}}{Z_{i2}+Z_2} V_B = \left(\underbrace{\frac{Z_{i1}}{Z_{i1}+Z_1}}_{\alpha_1} - \underbrace{\frac{Z_{i2}}{Z_{i2}+Z_2}}_{\alpha_2} \right) V_B$$

Due to unavoidable impedance mismatch, the two impedance ratios α_1 and α_2 are not equal and a common mode disturbance voltages generate a differential voltage.

Effect of the finite input impedances of the amplifier



$$V_{id} = \left(\frac{Z_{i1}}{Z_{i1} + Z_1} - \frac{Z_{i2}}{Z_{i2} + Z_2} \right) V_B \qquad V_B \cong Z_3 I_G$$

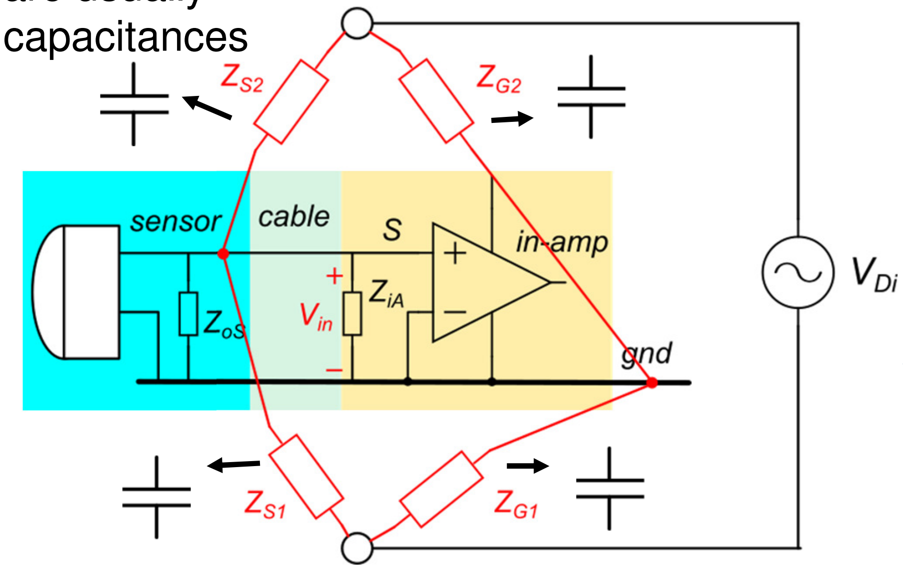
V_B can include the fundamental component of the AC power line (50 or 60 Hz, depending on country) but also harmonics at higher frequency and other disturbance signals from motors, DC-DC converters, etc,

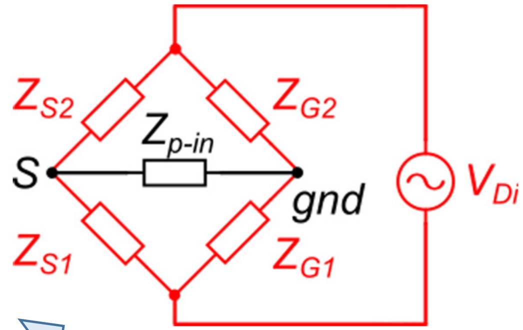
The amplifier input impedances Z_{i1} and Z_{i2} are mainly capacitive, while Z_1 and Z_2 may include both capacitive and resistive components.

Clearly, in the case that $Z_{i1}, Z_{i2} >> Z_1, Z_2$, the impedance ratios α_1 and α_2 are very close to 1 and their difference is close to zero. This is the case of infinite input amplifier that we have analyzed before, where the effect of V_B on V_{id} was null.

General case of no electrical continuity

These impedances are usually capacitances

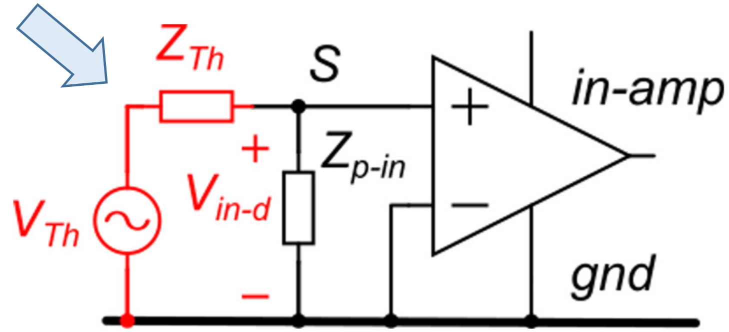




Circuit for calculation of the disturbance at the amplifier input

$$Z_{p-in} = Z_{oS} \| Z_{iA}$$

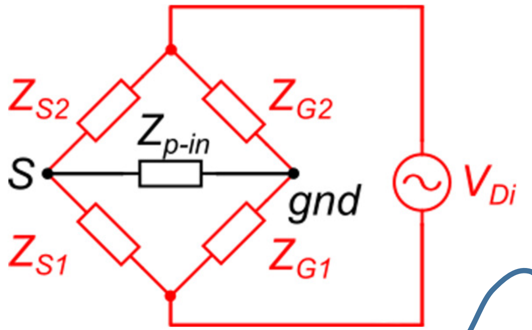
That can be further simplified, applying the Thevenin theorem at the bridge diagonal where *Zp-in* is placed. The Thevenin equivalent does not include *Zp-in*



Here, we represent a typical connection between amplifier and sensor ...

... and we add a disturbance voltage applied between two conductors. This disturbance can be the AC power line, but also have a different origin

General case of no electrical continuity



$$Z_{p-in} = Z_{oS} \parallel Z_{iA}$$

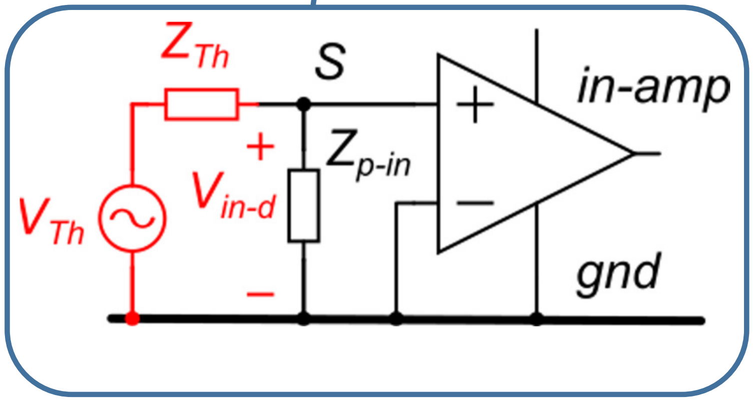
$$V_{Th} = V_{Di}\left(\frac{Z_{S1}}{Z_{S2}+Z_{S1}} - \frac{Z_{G1}}{Z_{G2}+Z_{G1}}\right)$$

$$Z_{th} = Z_{S1} \parallel Z_{S2} + Z_{G1} \parallel Z_{G2}$$

V_{TH} is zero only for:

$$\frac{Z_{S1}}{Z_{S2}} = \frac{Z_{G1}}{Z_{G2}}$$

which generally does not occur.



$$V_{in-d} = \frac{Z_{p-in}}{Z_{p-in}+Z_{th}} V_{th}$$

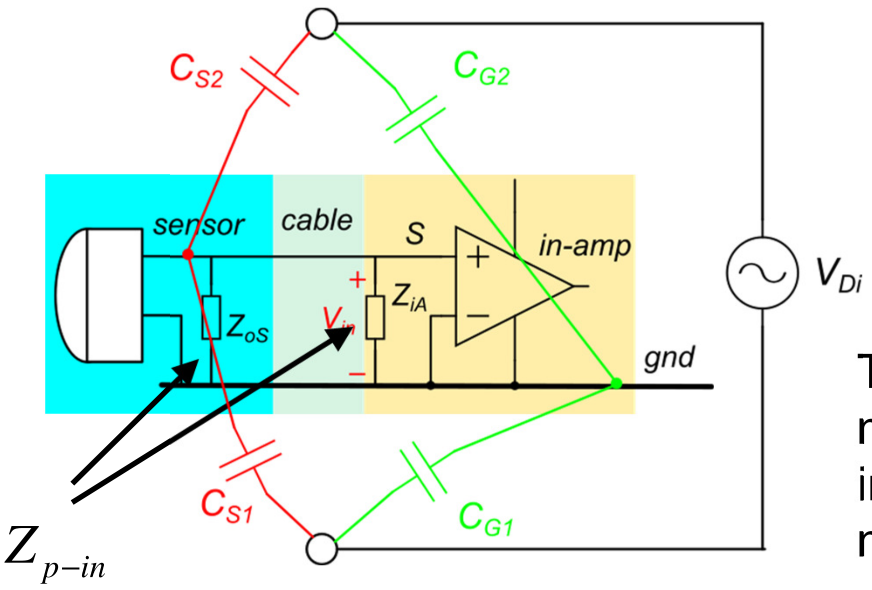
With a careful design:

$$\left|Z_{p-in}\right| << \left|Z_{th}\right|$$

$$V_{in-d} \cong \frac{Z_{p-in}}{Z_{th}} V_{th}$$

For a given $Z_{p\text{-}in}$ (sensor and amplifier), the higher Z_{th}, the smaller the input disturbance

Disturbance minimization: capacitive (electrostatic) coupling



$$V_{in-d} \cong \frac{Z_{p-in}}{Z_{th}} V_{th} \qquad Z_{th} = Z_{S1} \| Z_{S2} + Z_{G1} \| Z_{G2}$$

$$\frac{1}{j\omega(C_{S2}+C_{S1})} \qquad \frac{1}{j\omega(C_{G2}+C_{G1})}$$

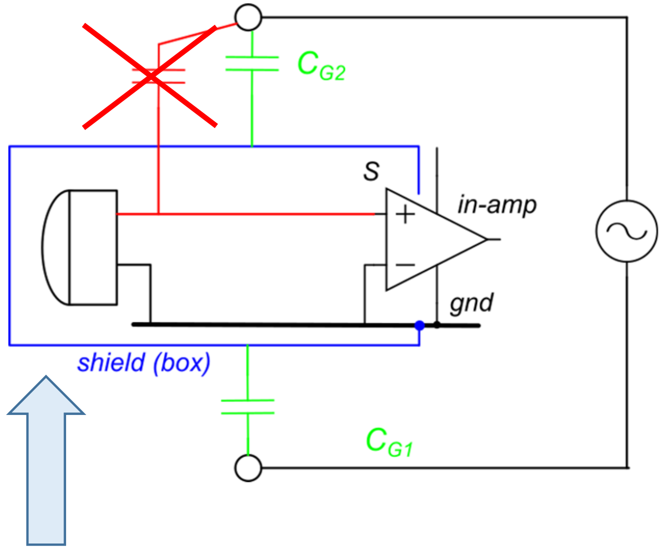
The magnitude of this component, due to the "hot" terminal, is much higher than the other, because capacitances that involve the *gnd* node (and all other nodes connected to it) are much larger.

$$Z_{th} \cong Z_{S1} \| Z_{S2}$$

In order to minimize the interference, we can maximize the impedance between the "hot terminal" and the disturbance conductors. This means reducing the related capacitances C_{S1} and C_{S2}.

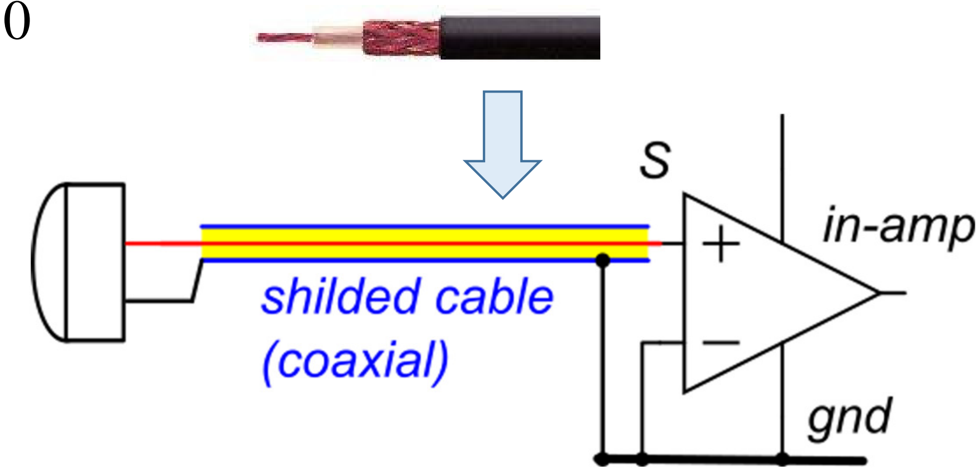
Mutual capacitance reduction: shielding

External conductors cannot produce fields inside the shield ("faraday cage")



$$C_{S2}, C_{S1} \rightarrow 0$$

$$Z_{th} \rightarrow \infty$$



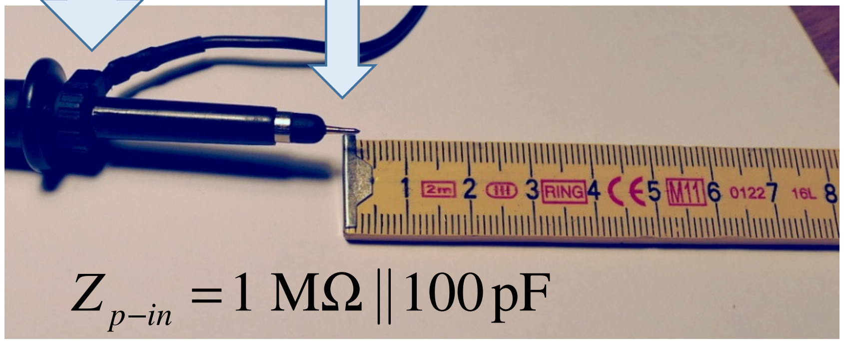
We add a conductive shield that wraps around the sensitive input node (and other sensitive nodes, if any)

For relatively long connections between the sensor and the amplifier, a shielded coaxial cable can be used to protect the internal "hot" terminal from interaction with disturbance conductors.

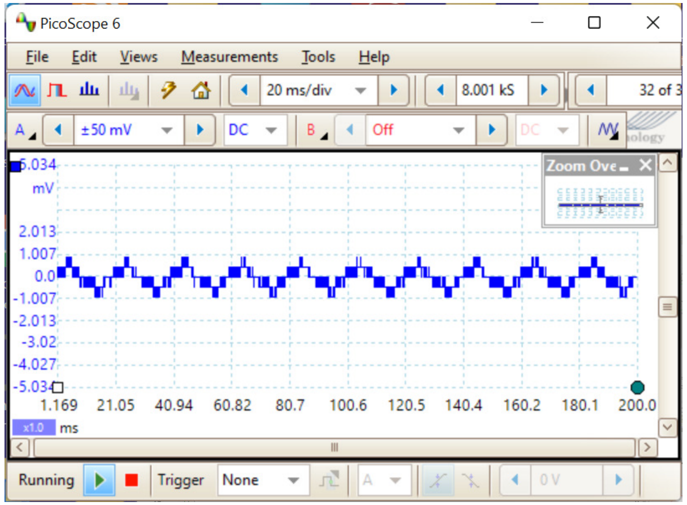
Example

Oscilloscope probe. The input "hot" terminal is shielded.

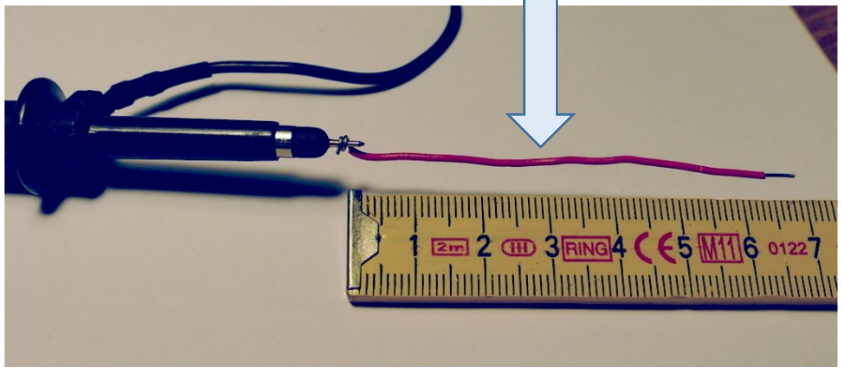
The exposed conductor is less than 1 cm long



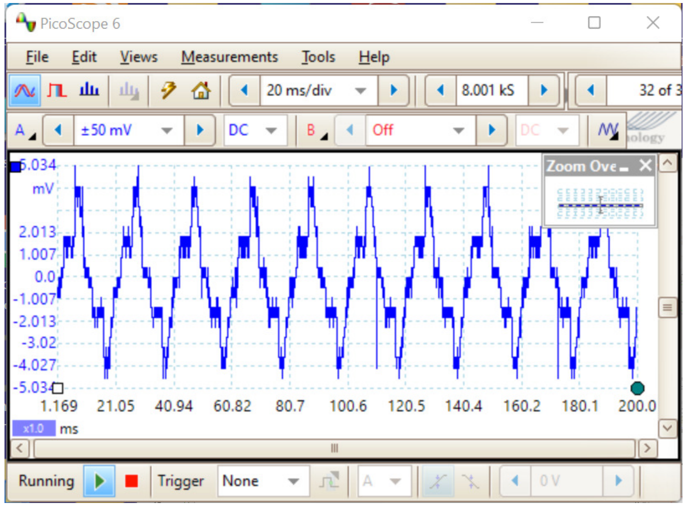
$$Z_{p-in} = 1\ \text{M}\Omega \,||\, 100\,\text{pF}$$



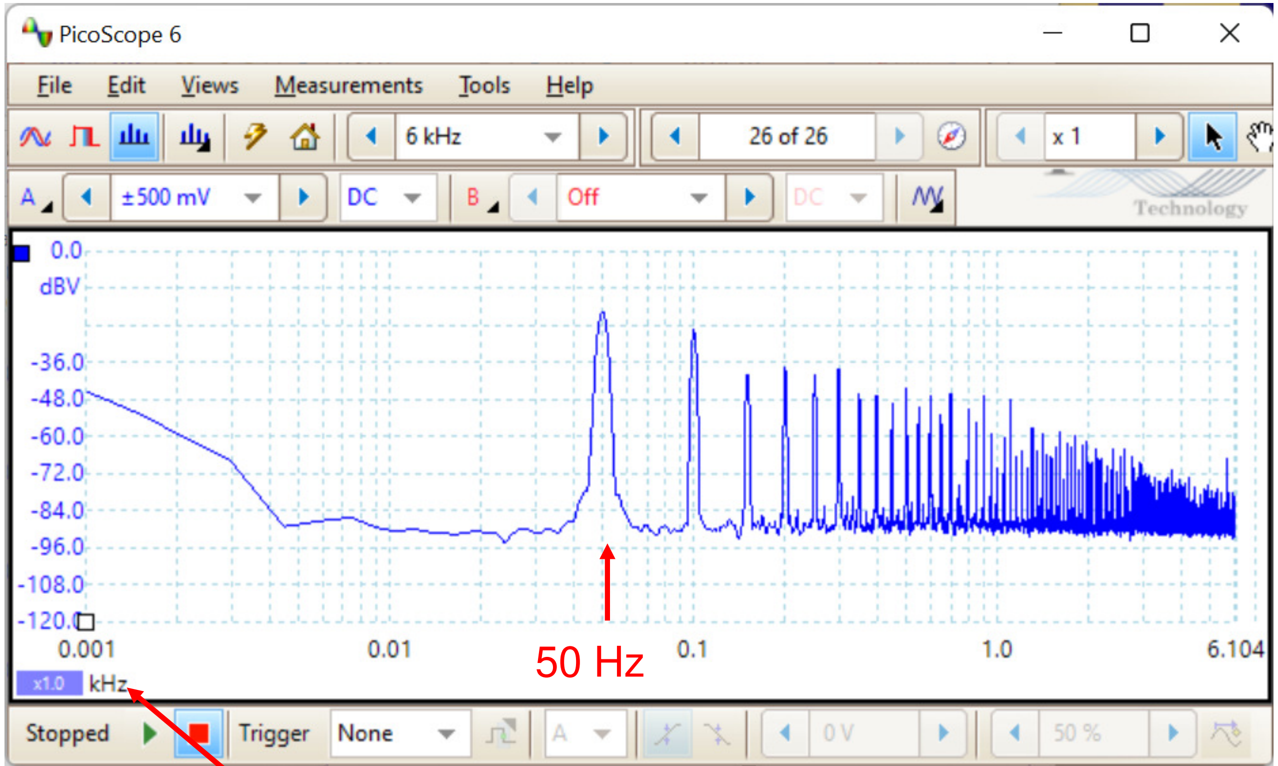
Just adding 6 cm of unshielded conductor ...



~10 mV p-p 50 Hz with strong harmonics



Spectral content of the disturbance voltage



horizontal scale: kHz

The voltage picked up from the AC power line by capacitive coupling is much more distorted than the original voltage, since high order harmonics find much less attenuation:

$$V_{in-d} \cong \frac{Z_{p-in}}{Z_{th}} V_{th}$$

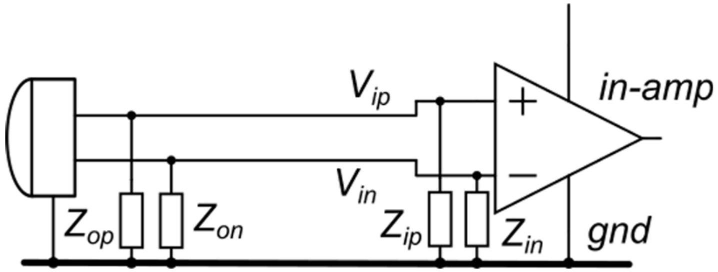
At low frequencies the resistive component dominates

$$Z_{p-in} \cong R_{p-in}$$

$$\cong \frac{1}{j\omega(C_{S2}+C_{S1})}$$

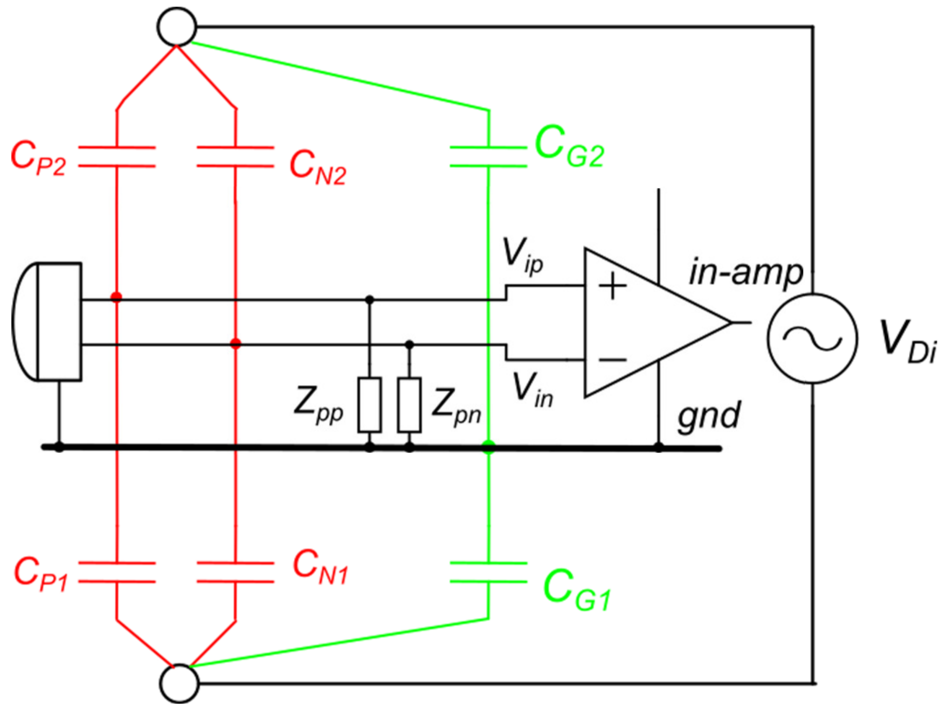
$$V_{in-d} \cong j\omega(C_{S2}+C_{S1}) R_{p-in} \cdot V_{Th}$$

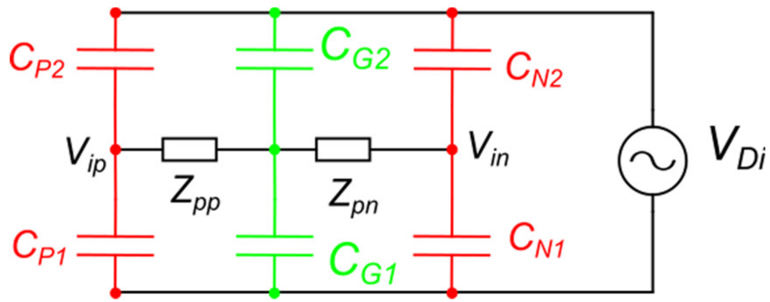
Advantage and limit of differential reading.



In a differential connection, the signal is the voltage difference between two wires, none of which is gnd.
The sensor has three terminals.

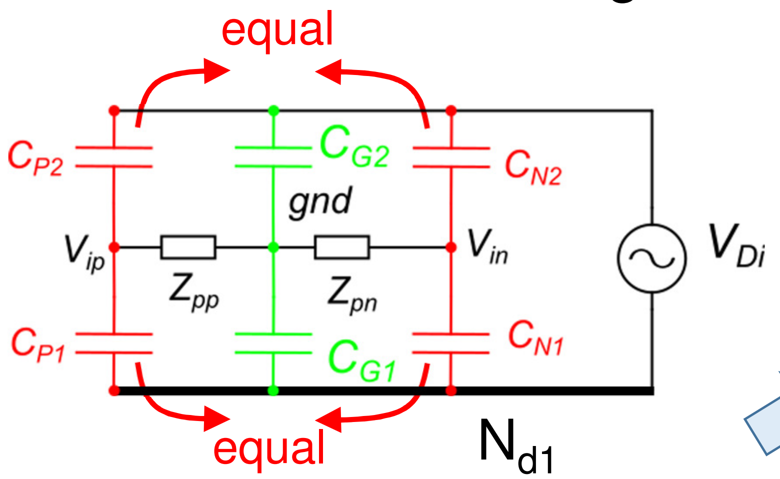
$$Z_{pp} = Z_{op} \parallel Z_{ip}$$
$$Z_{pn} = Z_{on} \parallel Z_{in}$$

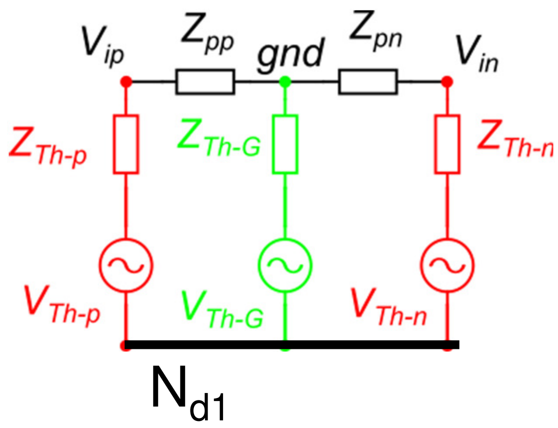




With a symmetrical routing of V_{ip} and V_{in}, we can obtain: $C_{P1}=C_{N1}$, $C_{P2}=C_{N2}$

Advantage and limit of differential reading.





Thanks to the symmetry:

$$V_{Th-p} \cong V_{Th-n}$$

$$Z_{Th-p} \cong Z_{Th-n}$$

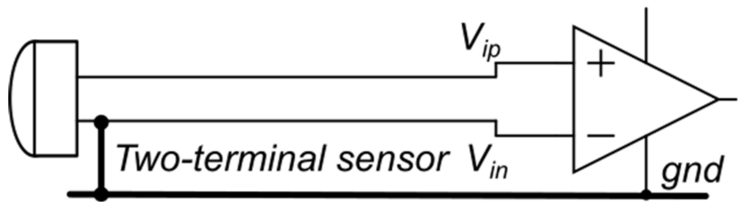
We apply three times the Thevenin equivalent between Nd1 and: V_{ip}, gnd, V_{in}, respectively.

Then, to obtain $V_{id}=V_{ip}-V_{in}=0$ we need a balanced source and balanced amplifier:

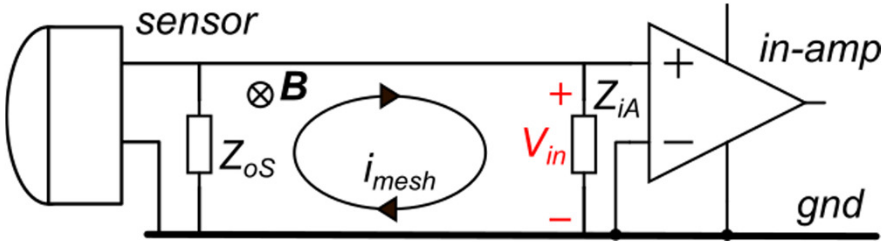
$$Z_{pp} = Z_{pn}$$

There are critical cases where it is not possible to have a balanced source.
A pseudo-differential configuration is not effective:

$$Z_{pp} \neq Z_{pn} = 0$$



Interference from variable magnetic fields



The loop formed by the mesh that includes the sensor output port and amplifier input port is subjected by an electromotive force given by:

$$V_{em} = -\frac{d\Phi}{dt}$$

For a sinusoidal magnetic field: $V_{em} = -j\omega\Phi$

The current in the loop is given by: $i_{mesh} = \dfrac{-j\omega\Phi}{Z_{oS} + Z_{iA}}$

The voltage at the amplifier input is then: $V_{in} = Z_{iA} i_{mesh} = -j\omega\Phi \dfrac{Z_{iA}}{Z_{oS} + Z_{iA}}$

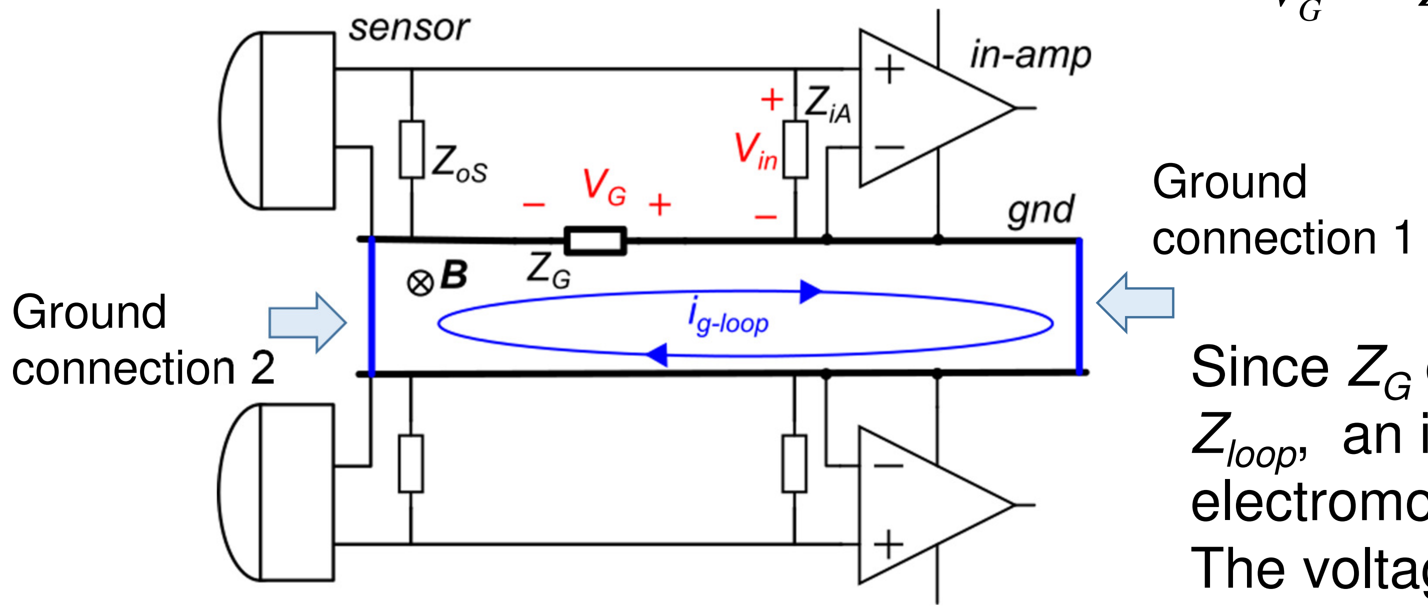
If $|Z_{iA}| >> |Z_{oS}|$ $\quad V_{in} \cong V_{em} = -j\omega\Phi$

In order to reduce the disturbance, it is necessary to reduce the area of all critical loops. Twisting the cables reduces the equivalent area of connection cables. Note that magnetic shield are much less effcetive than electrical ones.

Ground loops

The picture below depicts two reaout channels (two sensors). The ground of the two channels must be connected together in a single point. Connecting the grounds in two spatially separated points, creates a loop that can sustain considerably large currents.

$$V_G = -Z_G i_{g-loop} = j\omega\Phi \frac{Z_G}{Z_{loop}}$$



Z_{loop} is the series impedance of the whole loop.

Since Z_G can be a large fraction of Z_{loop}, an important portion of the electromotive force falls across Z_G. The voltage V_G gets added to the output signal of the sensor.