Why Things Don't Work –
Why S/N Theory Often Seems to be Irrelevant

There are many reasons why things don't work ...

1. Idiocy
2. Incompetence
3. Meetings
    (where decisions are made,
    but many participants are incompetent)

However, you might also encounter some technical problems:

Throughout the previous lectures it was assumed that the only sources of noise were

- random
- known
- in the detector, preamplifier, or associated components

In practice, the detector system will pick up spurious signals that are

- not random,
- but not correlated with the signal,

so with reference to the signal they are quasi-random.

⇒ Baseline fluctuations superimposed on the desired signal

⇒ Increased detection threshold, degradation of resolution

Important to distinguish between

- pickup of spurious signals, either from local or remote sources (clocks, digital circuitry, readout lines),
- self-oscillation
  (circuit provides feedback path that causes sustained oscillation due to a portion of the output reaching the input)

External Pickup is often the cause, but many problems are due to poor work practices or inappropriate equipment

1. Termination of Cables

Signals are transmitted from one unit to another through transmission lines, often coaxial cables or ribbon cables.

When transmission lines are not terminated with their characteristic impedance, the signals are reflected.

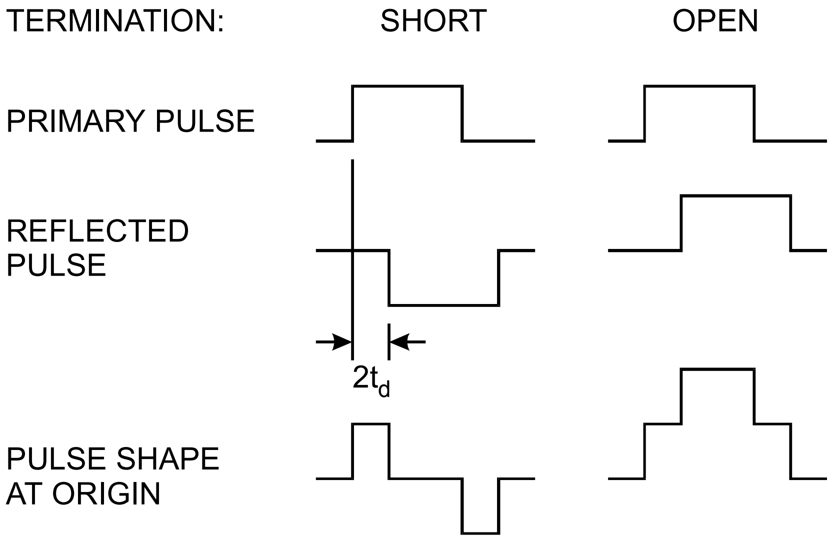
Reflections on Transmission Lines

Termination < Line Impedance:

Reflection with opposite sign

Termination > Line Impedance:

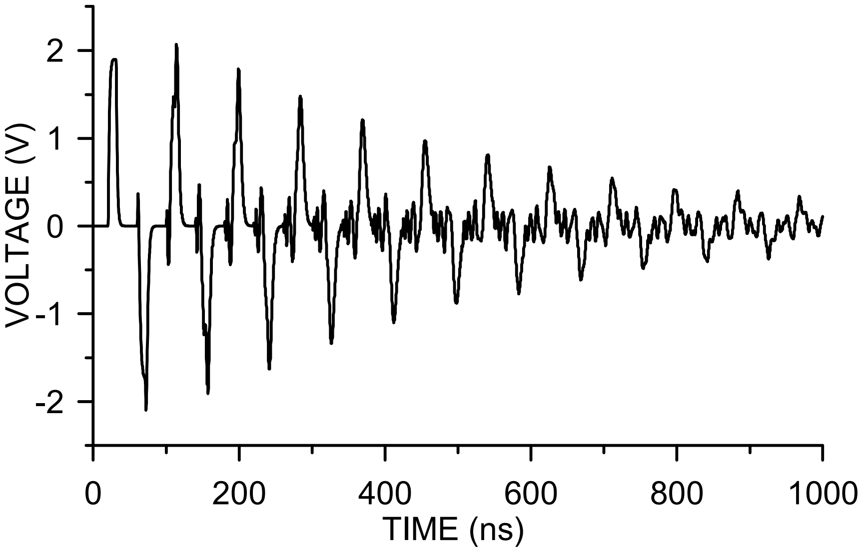
Reflection with same sign



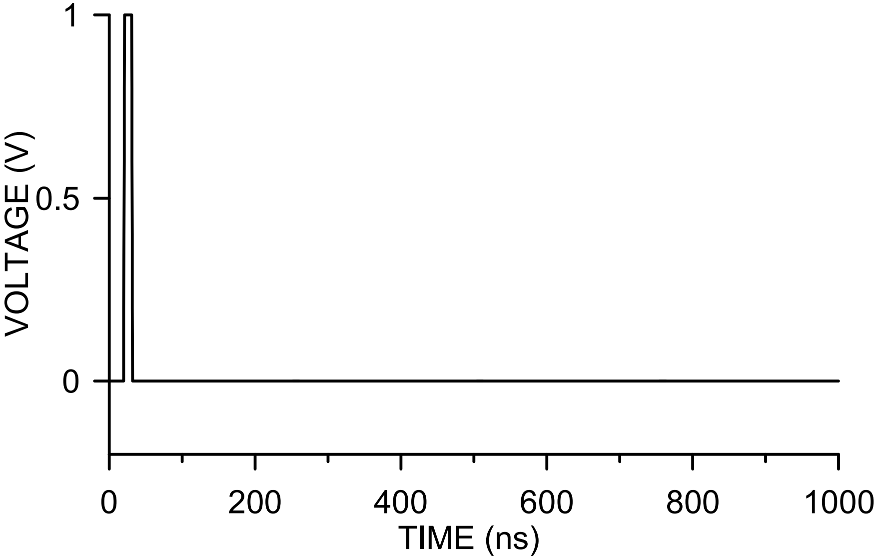
Example:

1 K in parallel with 30 pF is a typical input impedance for a shaping amplifier.

If feeding a counter, each signal pulse will be registered the multiple times, depending on the threshold setting.

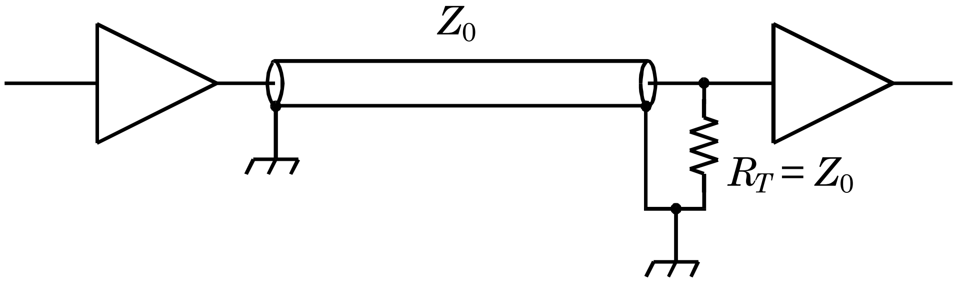


When the cable is properly terminated, reflections disappear.

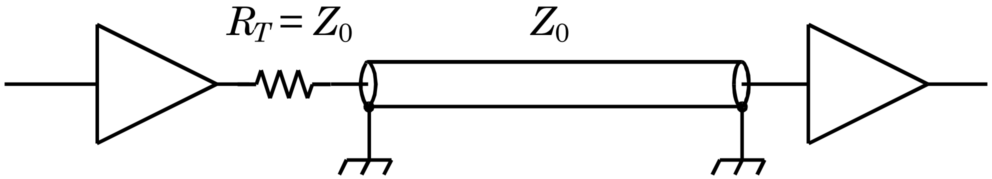


Two methods of terminating cables:

1. Parallel termination at receiving end



2. Series termination at sending end



In this configuration the original pulse is reflected at the receiving end, but the reflection is absorbed at the sending end, so it doesn't reappear at the receiver.

The series resistor feeding the transmission line forms a voltage divider that attenuates the pulse amplitude by a factor of 2.

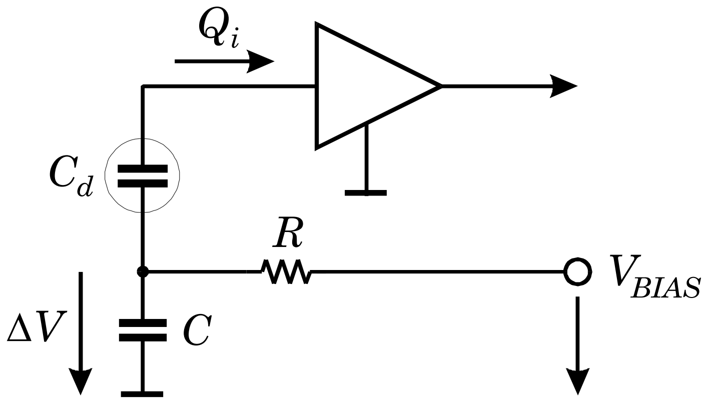
However, since the high impedance at the end of the cable causes a reflected pulse with the same amplitude, the pulse amplitude is doubled, so it is the same as the original.

Terminations are never perfect, especially at high frequencies (>10 ... 100 MHz), so in critical applications one can use both series and parallel termination. However, this does incur a 50% reduction in pulse amplitude.

In the >μs regime, amplifier inputs are usually high impedance, whereas timing amplifiers tend to be internally terminated (check!).

Noisy Detector Bias Supplies

The detector is the most sensitive node in the system.



Any disturbance ΔV on the detector bias line will induce charge in the input circuit.

$$\Delta Q = C_d \Delta V$$

$\Delta V = 10$ μV and 10 pF detector capacitance yield
$\Delta Q \approx$ 0.1 fC – about 600 el or 2 keV (Si).

Especially when the detector bias is low (<100V),
it is tempting to use a general laboratory power supply.

Frequently, power supplies are very noisy – especially old units.
The RC circuits in the bias line provide some filtering, but usually not enough for a typical power supply

Beware of switching power supplies. Well-designed switching regulators can be very clean, but most switchers are very noisy.

Spikes on the output can be quite large, but short, so that the rms noise specification may appear adequate.

⇒ **Use very low noise power supplies.**

Light Pick-Up

Every semiconductor detector is also a photodiode

Sources

- Room lighting (Light Leaks)
- Vacuum gauges

Interference is correlated with the power line frequency
(60 Hz in U.S., 50 Hz in Europe, Japan)

Pickup from incandescent lamps has twice the line frequency
(light intensity $\propto$ voltage squared)

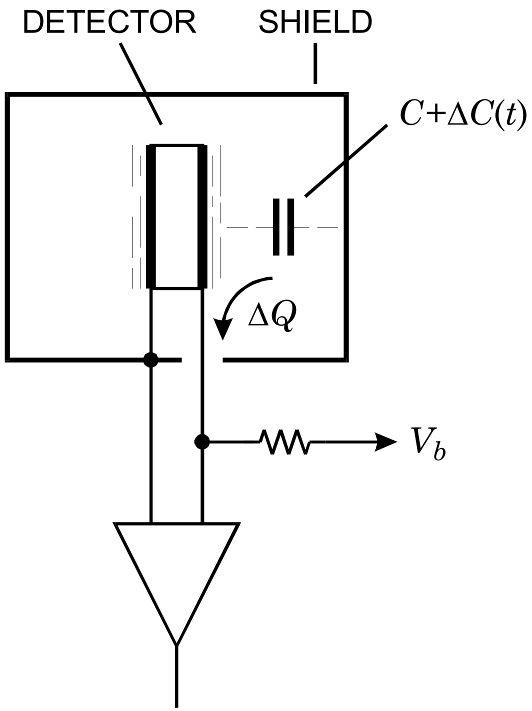
Diagnostics:

a) Inspect signal output with oscilloscope set to trigger mode “line”. Look for stationary structure on baseline. Analog oscilloscope better than digital.

b) Switch off light

c) Cover system with black cloth (preferably felt, or very densely woven – check if you can see through)

Microphonics



If the electrode at potential V_B vibrates with respect to the enclosure, the stray capacitance C is modulated by $\Delta C(t)$, inducing a charge

$$\Delta Q(t) = V_b \Delta C(t)$$

in the detector signal circuit.

Typically, vibrations are excited by motors
(vacuum pumps, blowers),
so the interference tends to be correlated with the line frequency.

Check with a) oscilloscope on line trigger
b) hand to feel vibrations

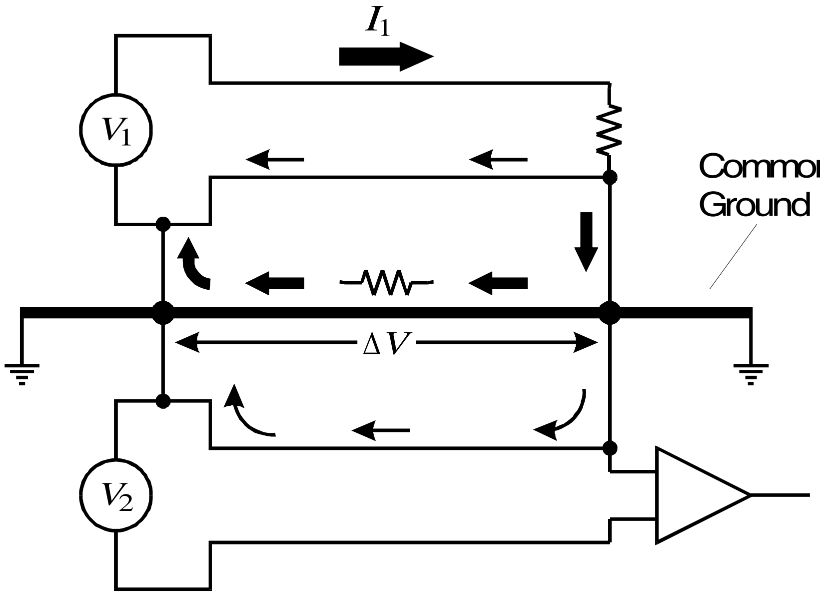
This type of pickup only occurs between conductors at different potentials, so it can be reduced by shielding the relevant electrode.

The shield should be at the same potential as the sensitive node.

Shared Current Paths – Grounding and the Power of Myth

Although capacitive or inductive coupling cannot be ignored, the most prevalent mechanism of undesired signal transfer is the existence of shared signal paths.

Mechanism:



A large alternating current I_1 is coupled into the common ground bus.

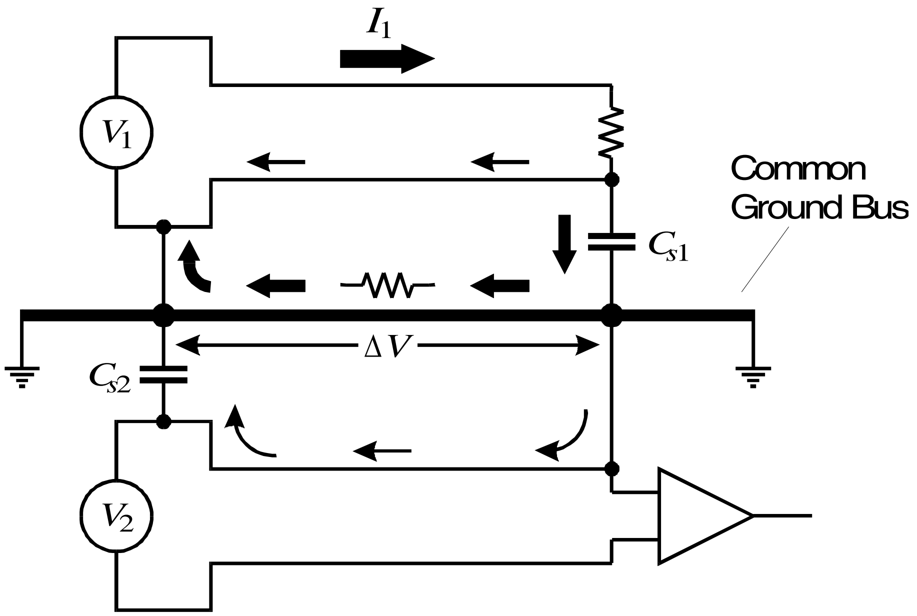
Although the circuit associated with generator V_1 has a dedicated current return, the current seeks the past of least resistance, which is the massive ground bus.

The lower circuit is a sensitive signal transmission path. Following the common lore, it is connected to ground at both the source and receiver.

The large current flowing through the ground bus causes a voltage drop ΔV, which is superimposed on the low-level signal loop associated with V_2 and appears as an additional signal component.

- Cross-coupling has *nothing to do with grounding per se*, but is due to the common return path. However, the common ground caused the problem by establishing the shared path.

In systems that respond to transients (i.e. time-varying signals) rather than DC signals, secondary loops can be closed by capacitance.
A DC path is not necessary.



The loops in this figure are the same as shown before, but the loops are closed by the capacitances C_{s1} and C_{s2}. Frequently, these capacitances are not formed explicitly by capacitors, but are the stray capacitance formed by a power supply to ground, a detector to its support structure (as represented by C_{s2}), etc. For AC signals the inductance of the common current path can increase the impedance substantially beyond the DC resistance, especially at high frequencies.

This mode of interference occurs whenever spurious voltages are introduced into the signal path and superimpose on the desired signal.

Remedial Techniques

1. Reduce impedance of the common path

⇒ Copper Braid Syndrome

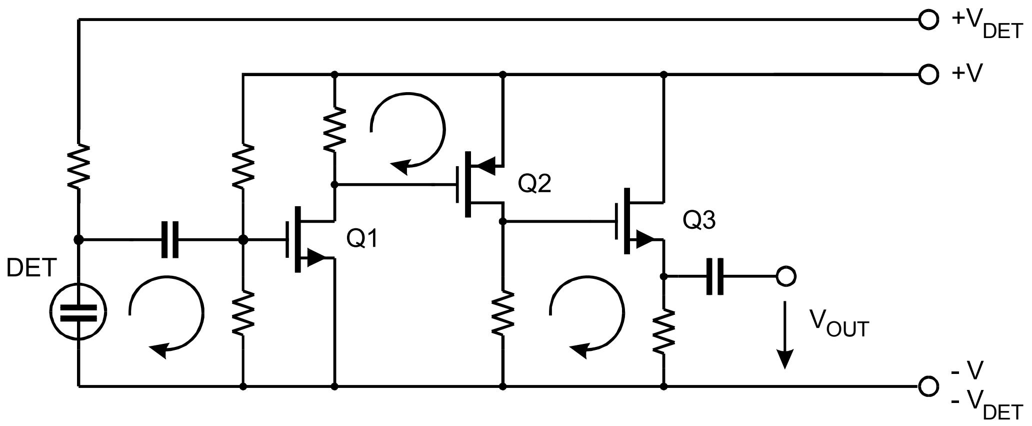
Colloquially called “improving ground”.

Sometimes fortuitously introduces an out-of-phase component of the original interference, leading to cancellation.

Rather haphazard, poorly controlled ⇒ continual surprises

2. Avoid Grounds

Circuits rely on current return paths, not a ground connection!



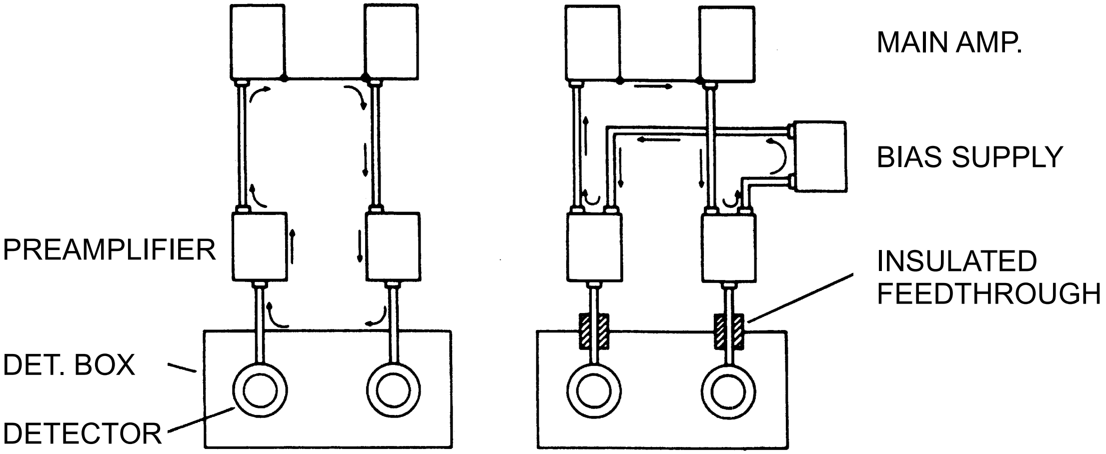
In transferring from stage to stage the signal current flows through local return loops.

1. At the input the detector signal is applied between the gate and source of Q1
2. At the output of Q1 the signal is developed across the load resistor in the drain of Q1 and applied between the gate and source of Q2.
3. The output of Q2 is developed across the load resistor in its drain and applied across the gate and source resistor and load.

Note that – disregarding the input voltage divider that biases Q1 – varying either $+V$ or $-V$ does not affect the local signals.

Breaking parasitic signal paths

Example:



The configuration at the left has a loop that includes the most sensitive part of the system – the detector and preamplifier input.

By introducing insulated feed-throughs, the input loop is broken.

Note that a new loop is shown, introduced by the common detector bias supply. This loop is restricted to the output circuit of the preamplifier, where the signal has been amplified, so it is less sensitive to interference.

- Note that the problem is not caused by loops *per se*, i.e. enclosed areas, but by the multiple connections that provide entry paths for interference.

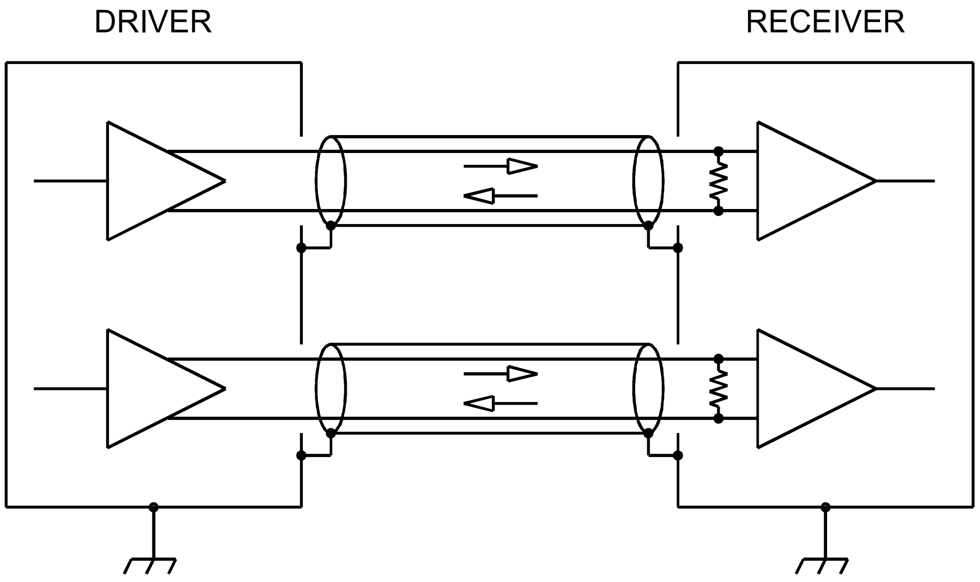
- Although not shown in the schematic illustrations above, both the "detector box" (e.g. a scattering chamber) and the main amplifiers (e.g. in a NIM bin or VME crate) are connected to potential interference sources, so currents can flow through parts of the input signal path.

Breaking shared signal paths, cont'd

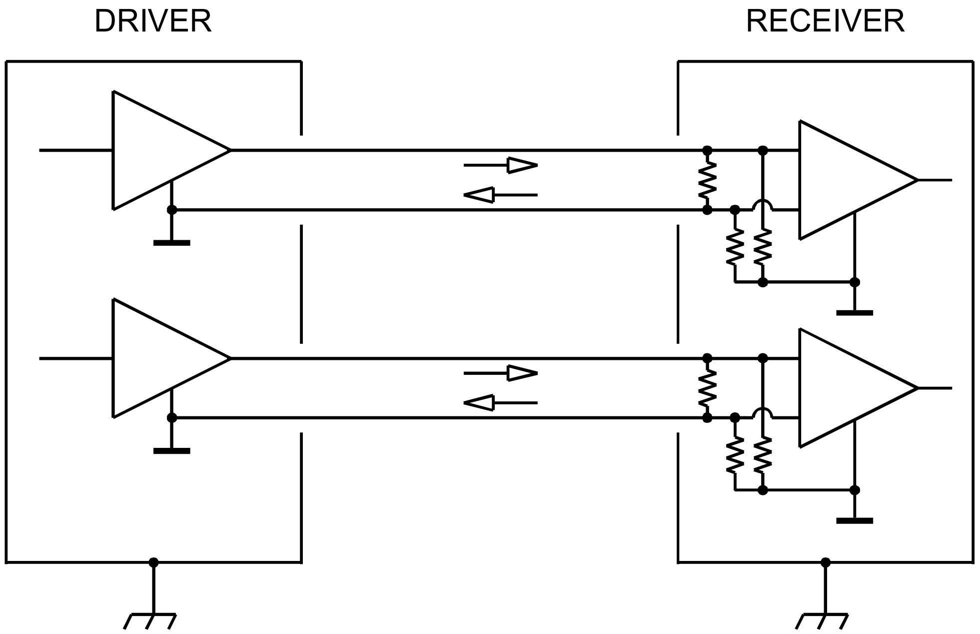
1. Differential Receivers

Besides providing common mode noise rejection, differential receivers also allow "ground free" connections.

Ideal configuration using differential drivers and receivers:



Technique also usable with single-ended drivers:



At the receiver input high-value resistors to ground provide potential referencing between the transmitter and receiver to avoid exceeding the common mode range of the receiver.

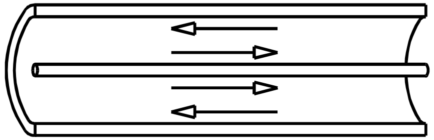
The transmission line is terminated by the shunt resistor (typ. 100 Ω)

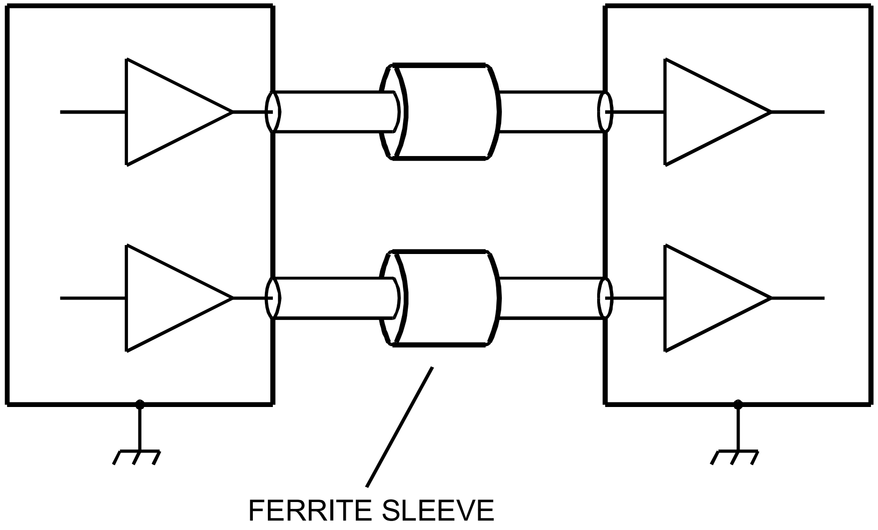
2. Insert high impedances

Ferrite sleeves block
common mode currents.

Signal current in coax line flows on

- outer surface of inner conductor
- inner surface of shield.





Net field at *outer surface* of shield is zero. ⇒ Ferrite sleeve does not affect signal transmission.

Common mode currents in the coax line (current flow in same direction on inner and outer conductor)

or

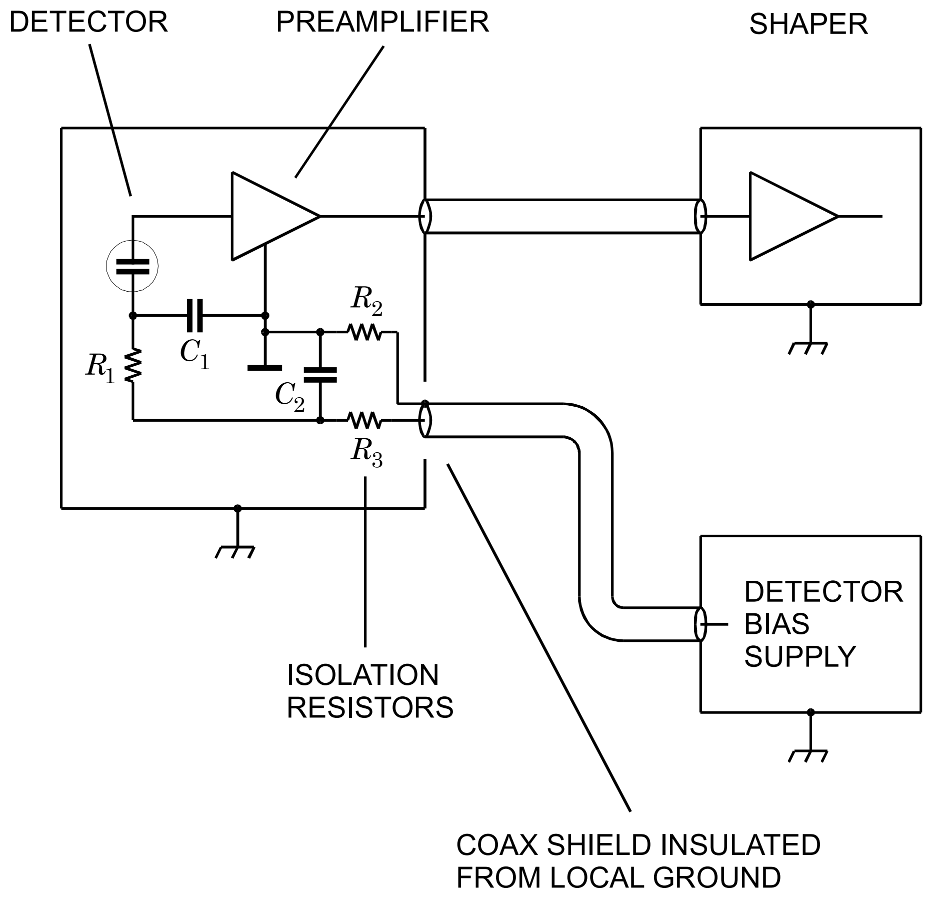
current components flowing only on the outside surface of the shield (“ground loops”)
will couple to the ferrite and be suppressed.

Ferrite material must be selected to present high impedance at relevant frequencies.

Technique can also be applied to twisted-pair ribbon cables.

Series resistors isolate parasitic ground connections.

Example: detector bias voltage connection



Isolation resistors can also be mounted in an external box that is looped into the bias cable. Either use an insulated box or be sure to isolate the shells of the input and output connectors from another.

A simple check for noise introduced through the detector bias connection is to use a battery.

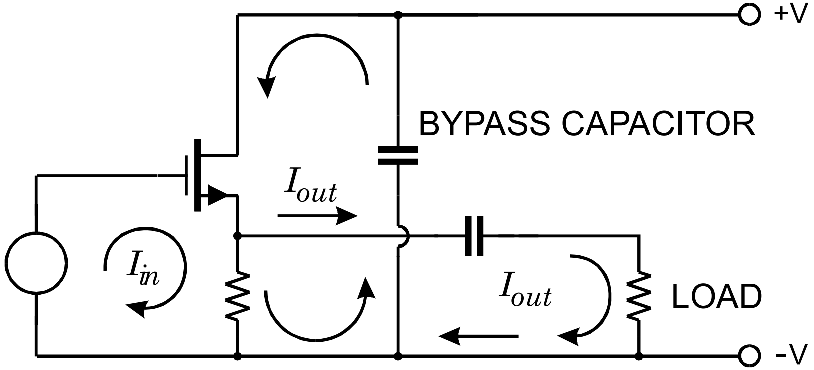
“Ground loops” are often formed by the third wire in the AC power connection. Avoid voltage differences in the “ground” connection by connecting all power cords associated with low-level circuitry into the same outlet strip.

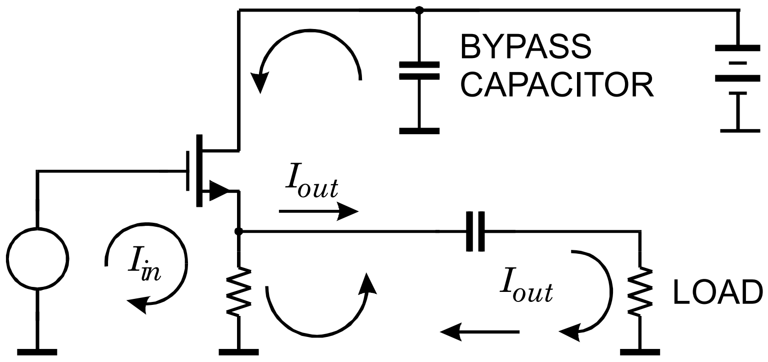
Ground returns are also critical at the circuit level.

Currents in output drivers:

In addition to the signal currents I_{in} and I_{out}, the drain current is also changing with the signal and must return to the source. Since the return through the power supply can be remote and circuitous, a well-defined AC return path is provided by the bypass capacitor.

Since the input and output signal voltages are usually referenced to the negative supply rail, circuits commonly configure it as a common large area bus, the “ground”, and all nodes are referenced to it.





Since the “ground” is a large area conducting surface – often a chassis or a ground plane – with a “low” impedance, it is considered to be an equipotential surface.

The assumption that “ground” is an equipotential surface is not always justified.

For high frequency signals (> 1 MHz) it is PRACTICALLY NEVER justified.

At high frequencies current flows only in a thin surface layer (“skin effect”).

The skin depth in aluminum is ~100 μm at 1 MHz. A pulse with a 3 ns rise-time will have substantial Fourier components beyond 100 MHz, where the skin depth is 10 μm.

$\Rightarrow$ Even large area conductors can have substantial resistance!

Example: a strip of aluminum, 1 cm wide and 5 cm long
has a resistance of ~20 mΩ at 100 MHz (single surface, typical Al alloy)

100 mA $\Rightarrow$ 2 mV voltage drop,

which can be much larger than the signal.

The resistance is determined by the ratio of length to width, i.e. a strip 1 mm wide and 5 mm long will show the same behavior.

Inductance can increase impedances much beyond this value!

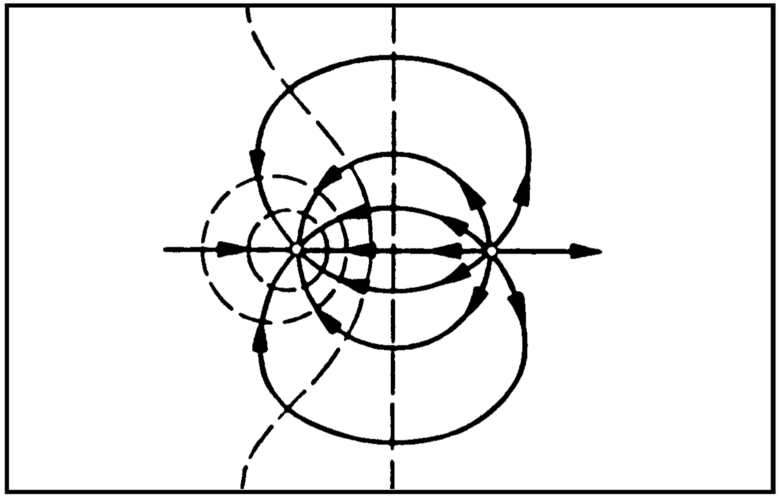
Consider a current loop closed by two connections to a ground plane.

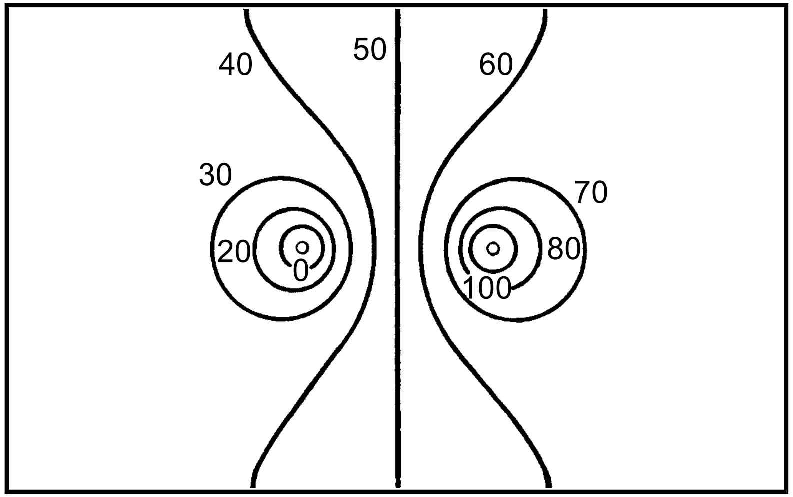
Current distribution around the two connection points

The dashed lines indicate equipotential contours.

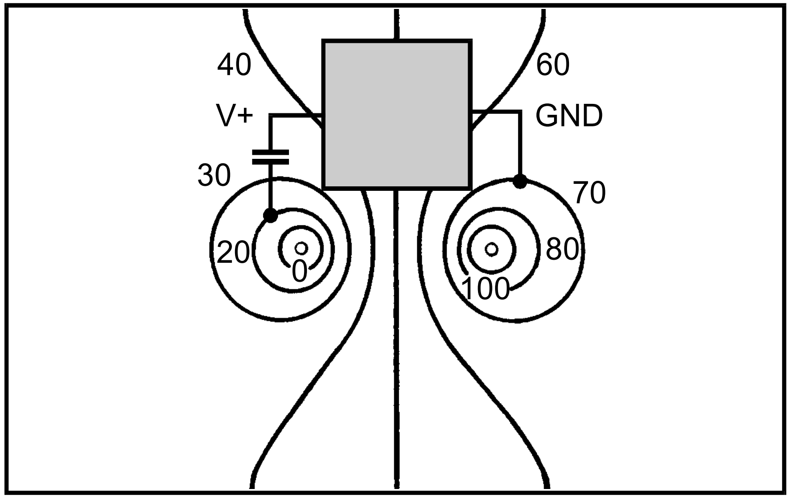
Assume a total drop of 100 mV.

The resulting potential distribution is shown below.

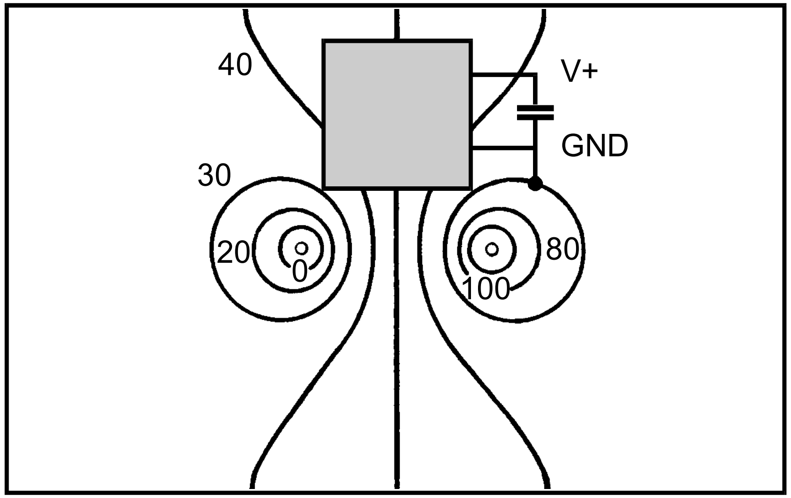




Mounting a circuit block (an IC, for example) with ground and bypass connections as shown below introduces a 50 mV voltage drop in the "ground" path.

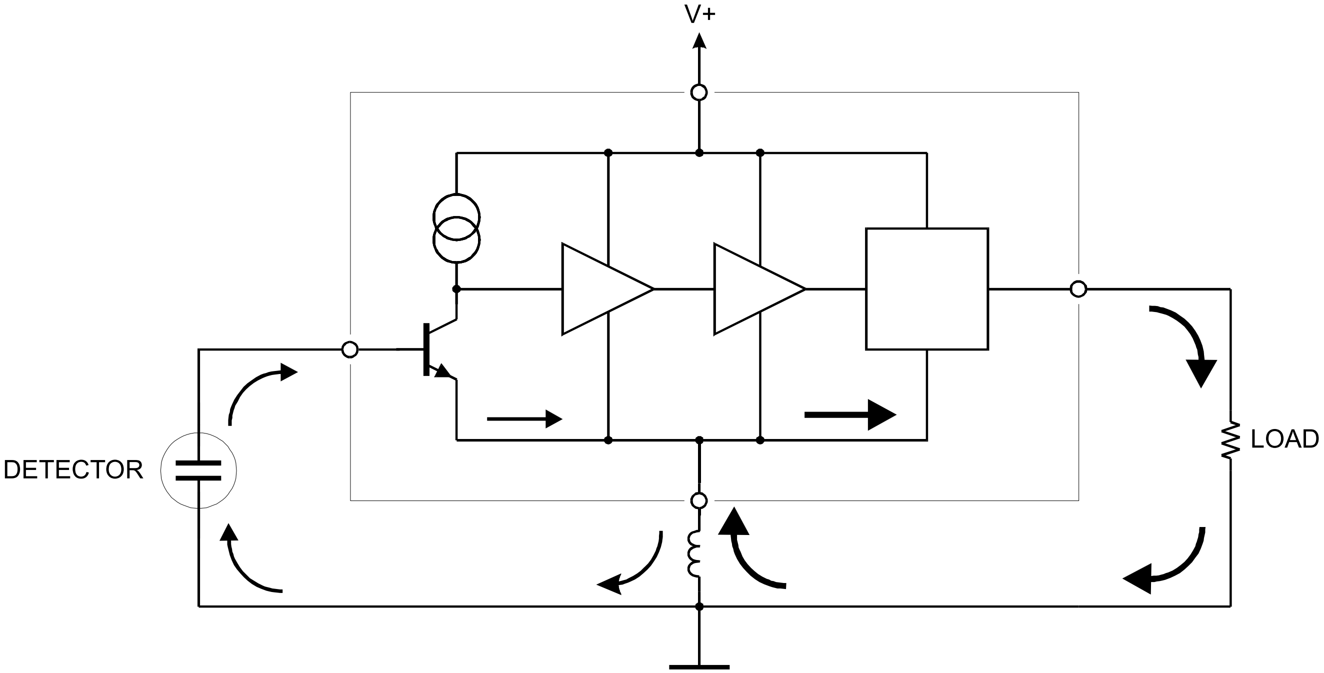


Direct connection of the bypass capacitor between the V+ and GND pads avoids pickup of the voltage drop on the ground plane.



“Ground” Connections in Multi-Stage Circuits

IC combining a preamplifier, gain stages and an output driver:

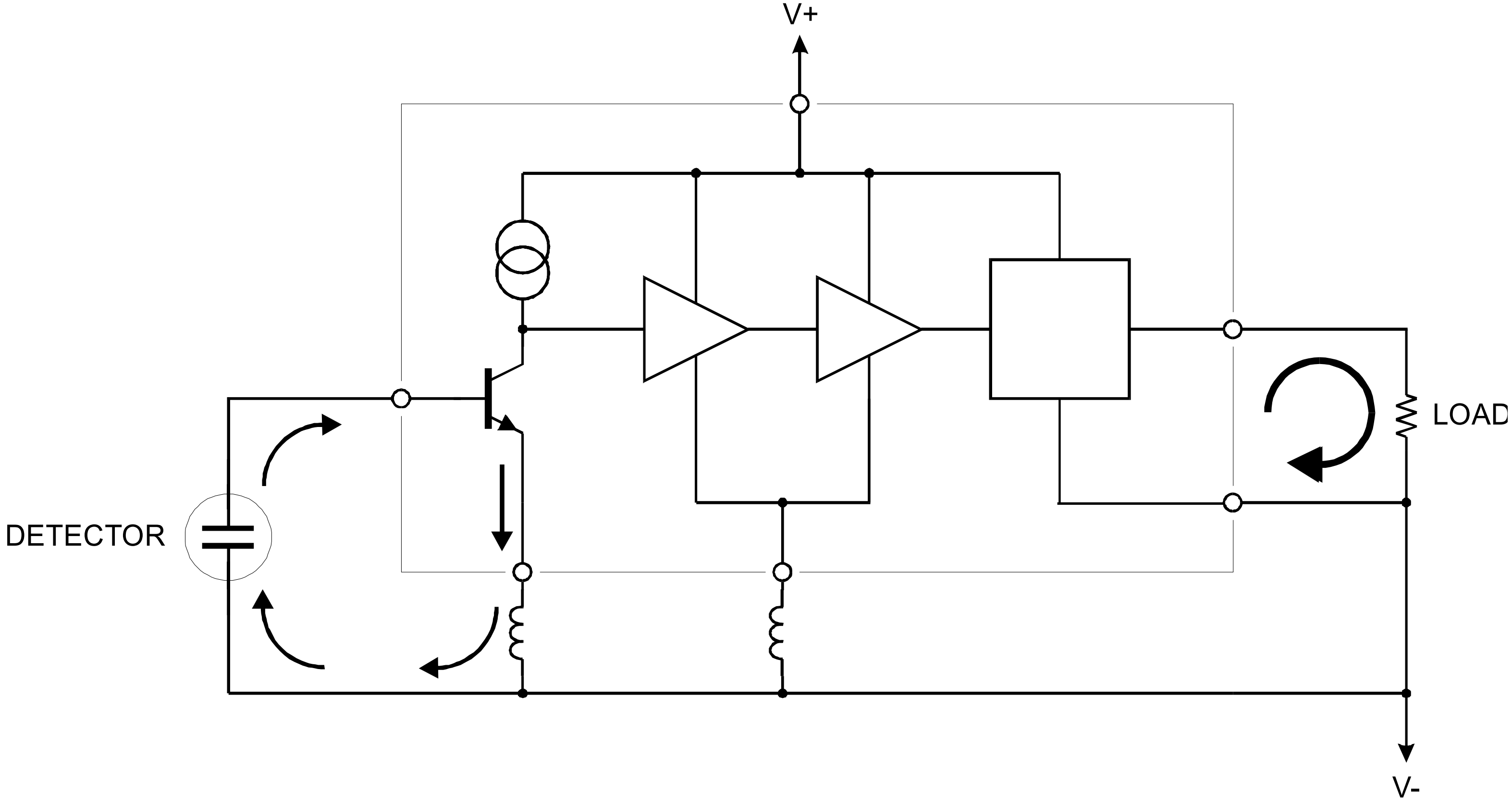


The output current is typically orders of magnitude greater than the input current (due to amplifier gain, load impedance).

Combining all ground returns in one bond pad creates a shared impedance (inductance of bond wire).

This also illustrates the use of a popular technique – the “star” ground – and its pitfalls.

Separating the “ground” connections by current return paths routes currents away from the common impedance and constrains the extent of the output loop, which tends to carry the highest current.

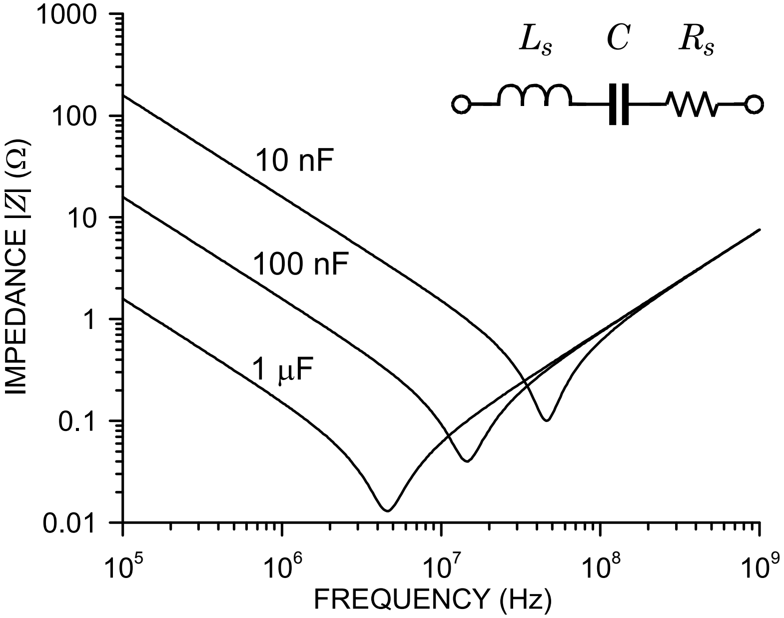


Choice of Capacitors

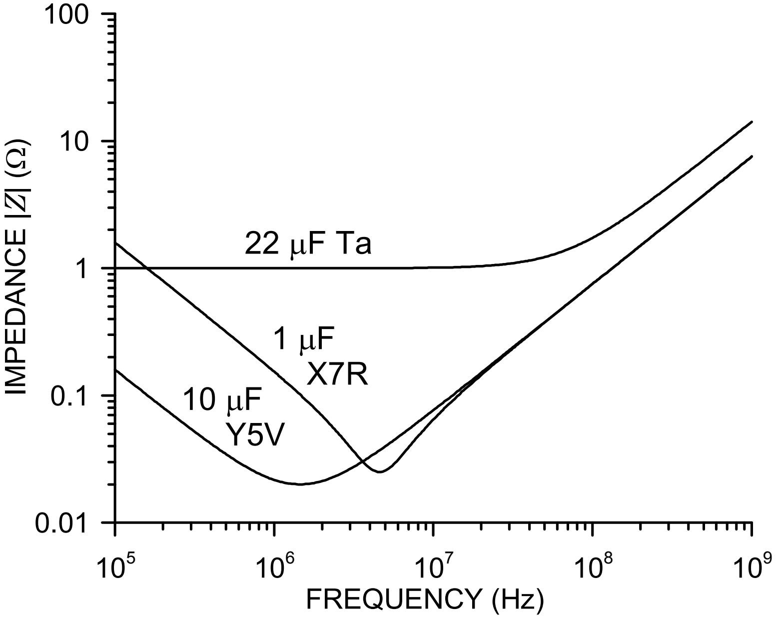
Capacitors are often in signal return paths. As bypass capacitors they must buffer large current pulses.

All capacitors form a series resonant circuit. Above the resonance frequency they act inductive. The loss resistance (equivalent series resistance, ESR) limits the impedance at resonance.

Impedance of X7R ceramic chip capacitors



Comparison between X7R, Y5V ceramic and Tantalum chip capacitors.



Y5V has large voltage dependence, typ. ~20% of nominal capacitance at rated voltage. X7R better.

2. Local Referencing

Noise currents on the cooling or support structures can couple to the detector input node.

⇒ Keep stave and module at same high-frequency potential

Keep mounting capacitance small,

Control spurious signals on mount

Easier said than done.

Just one example for a common challenge.

Very important!

Often the rationale for “grounding”, but think of the physical mechanisms before blindly following recipes.