VI. 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.

$\Rightarrow$ Baseline fluctuations superimposed on the desired signal

$\Rightarrow$ 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.
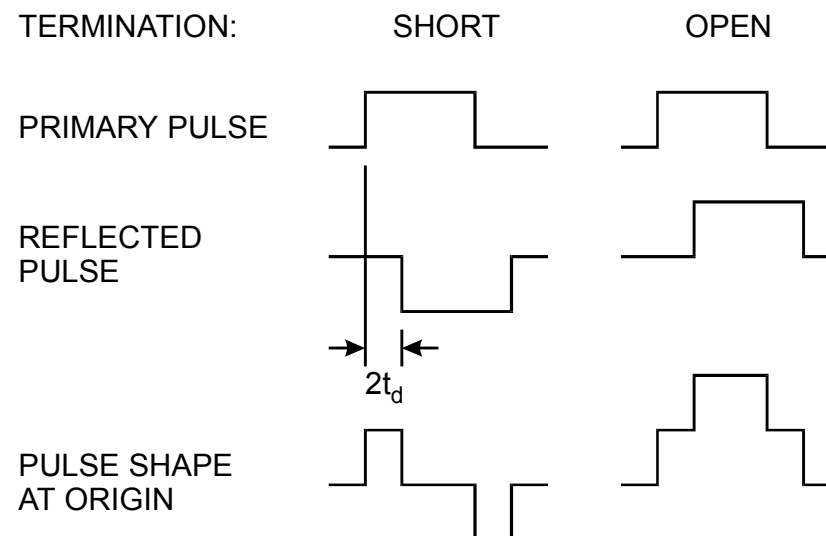
Reflections on Transmission Lines

Termination < Line Impedance:

   Reflection with opposite sign

Termination > Line Impedance:

      Reflection with same sign

TERMINATION: SHORT   OPEN

PRIMARY PULSE

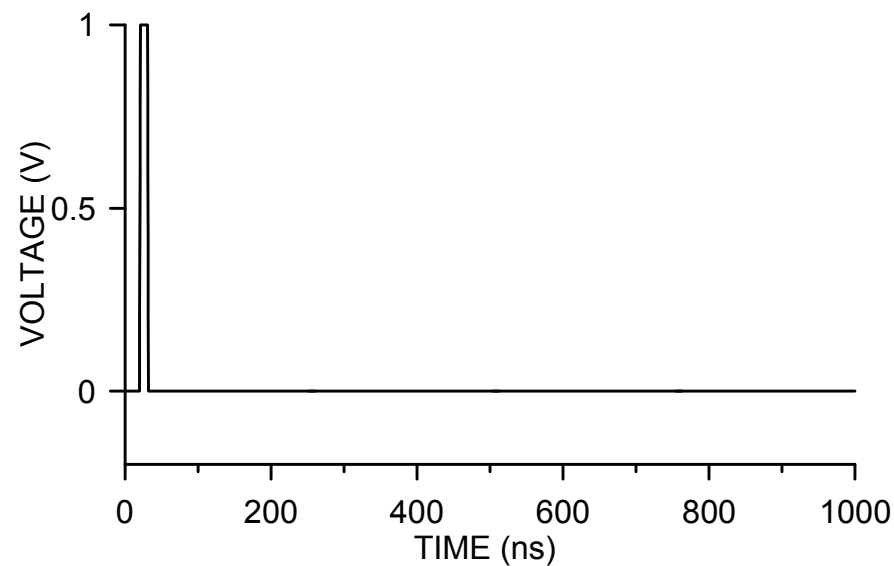REFLECTED PULSE

$2t_d$

PULSE SHAPE AT ORIGIN

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.
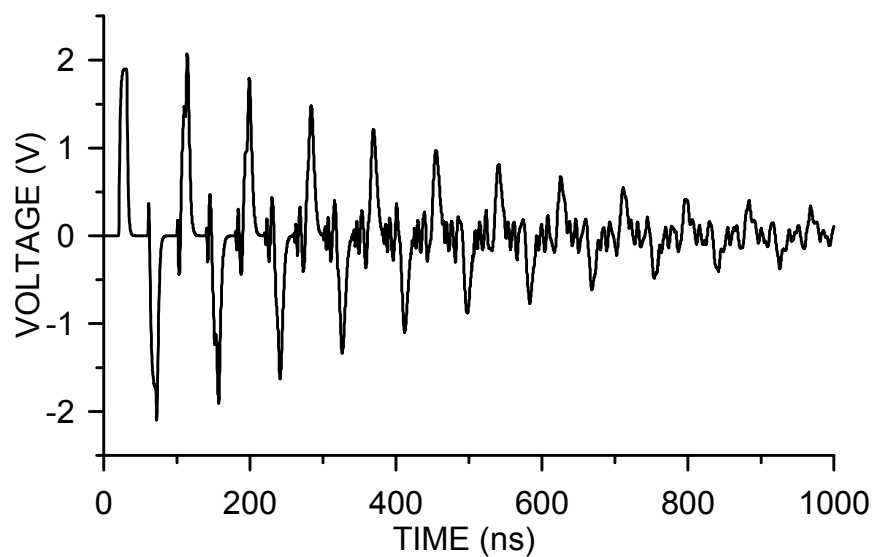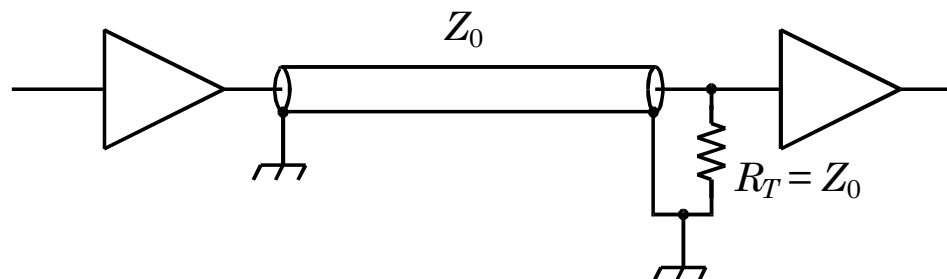
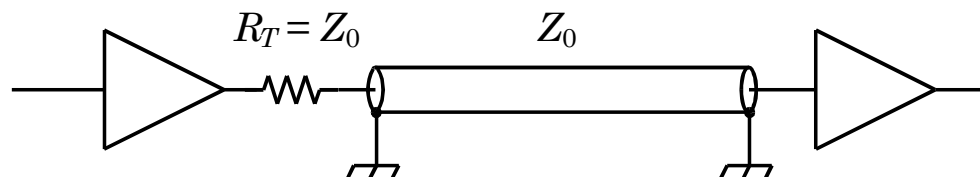When the cable is properly terminated, reflections disappear.

Two methods of terminating cables:

1. Parallel termination at receiving end

Z_0

$R_T = Z_0$

2. Series termination at sending end

$R_T = Z_0$ Z_0

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 $>\mu s$ 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.

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

$\Delta V = 10\ \mu V$ 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.

$\Rightarrow$ **Use very low noise power supplies.**
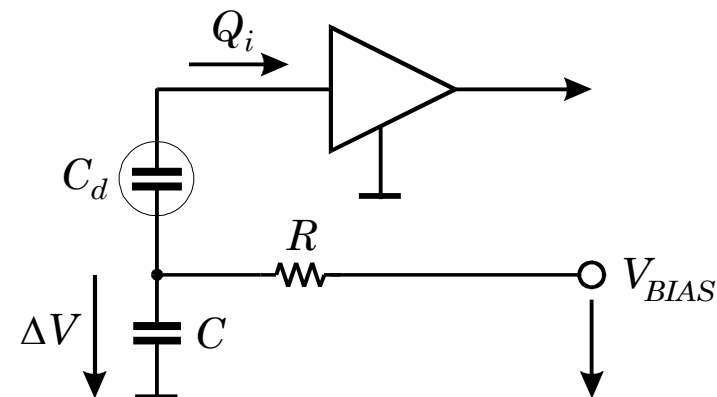
Common Types of Interference

1. Light Pick-Up

Critical systems:

- Photomultiplier tubes

- Semiconductor detectors
  (all semiconductor detectors
  are photodiodes)

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)

2. Microphonics

DETECTOR   SHIELD

$C+\Delta C(t)$

ΔQ

V_b

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.

    a) intermediate shield at electrode potential

    b) in coaxial detectors, keep outer electrode at 0 V.
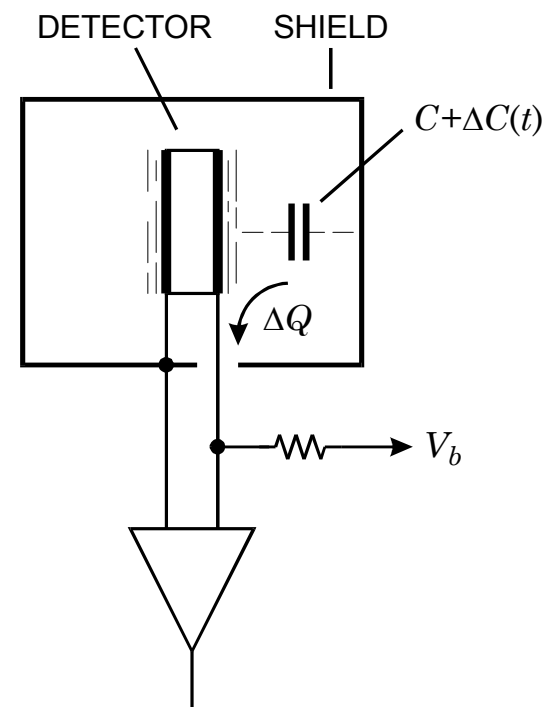
3. RF Pickup

All detector electronics are sensitive to RF signals.

The critical frequency range depends on the shaping time. The gain of the system peaks at

$$f \approx \frac{1}{2\pi\tau}$$

and high-gain systems will be sensitive over a wide range of frequencies around the peaking frequency.

Typical sources:

- Radio and TV stations
  AM broadcast stations: 0.5 – 1.7 MHz
  FM broadcast stations: ~ 100 MHz
  TV stations: 50 – 800 MHz

- Induction furnaces (13.6, 27, 40 MHz)

- Accelerators

  ⇒   Sine Waves

- Computers (10's to 100's MHz)

- Video Displays (10 – 100 kHz)

- Radar (GHz)

- Internal clock pulses (e.g. digital control, data readout)

  ⇒   Pulses
      (or recurring damped oscillations)

Pulsed UHF or microwave emissions can affect low-frequency circuitry by driving it beyond linearity (the bandwidth of the preamplifier can be much greater than of the subsequent shaper).

Diagnostic Techniques

a) Inspect analog output on an oscilloscope.

Check with different trigger levels and deflection times and look for periodic structure on the baseline.

Pickup levels as low as 10% of the noise level can be serious, so careful adjustment of the trigger and judicious squinting of the eye is necessary to see periodic structure superimposed on the random noise.

Again, an "old fashioned" analog oscilloscope is best.
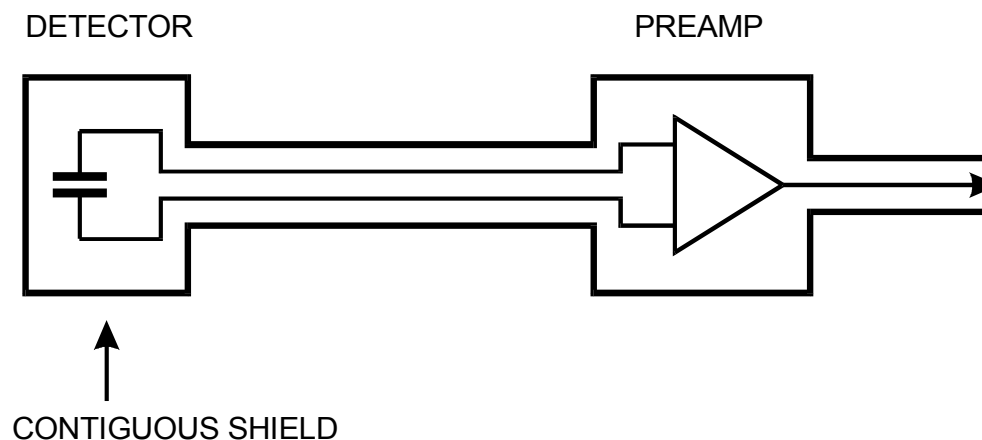

b) Inspect output with a spectrum analyzer

This is a very sensitive technique.

Indeed, for some it may be too sensitive, as it tends to show signals that are so small that they are irrelevant.

Ascertain quantitatively what levels of interfering signals vs. frequency are important.

Remedial Techniques

a) Shielding

DETECTOR   PREAMP

CONTIGUOUS SHIELD

Conducting shield attenuates an incident electromagnetic wave because of

- Reflection of the incident wave $\quad E_{0r} = E_0 \left(1 - \dfrac{Z_{shield}}{Z_0} \right) \quad$ where $\quad Z_0 = \sqrt{\dfrac{\mu}{\varepsilon}} = 377\ \Omega$

  is the impedance of free space.

  The impedance of the conductor is very low, so most of the incident wave is reflected.

  This mechanism is only operative in the far field (distances $> \lambda$ from source).

- Attenuation of the absorbed wave

The absorbed wave gives rise to a local current, whose field counteracts the primary excitation.

The net current decreases exponentially as the wave penetrates deeper into the medium

$$i(x) = i_0 e^{-x/\delta}$$

where i_0 is the current at the surface of the conductor and

$$\delta = \frac{1}{2 \cdot 10^{-4}} \left[\sqrt{\text{cm} \cdot \text{s}^{-1}} \right] \sqrt{\frac{\rho}{\mu_r f}}$$

is the penetration depth or "skin depth".

μ_r and ρ are the permeability and resistivity of the conductor and
f is the frequency of the incident wave.

In aluminum, $\rho = 2.8 \ \mu\Omega \cdot \text{cm}$ and $\mu_r = 1$, so at $f = 1$ MHz

the skin depth $\delta = 84 \ \mu\text{m} \approx 100 \ \mu\text{m}$.

The skin depth decreases with the square root of
- increasing frequency
- decreasing resistivity (increasing conductivity)

If the shield is sufficiently thick, the skin effect isolates the inner surface of a shielding enclosure from the outer surface.

However, this isolation only obtains if no openings in the shield allow the current to flow from the outside to the inside.

External fields can penetrate if openings > λ /1000 (diameter of holes, length of slots).

To maintain the integrity of the shield,

- covers must fit tightly with good conductivity at the seams (beware of anodized aluminum!),

- all input and output lines (signal and DC supplies) must have good shield connections,

- shield coverage of coax or other cables >90%, and

- connectors must maintain the integrity of the shield connection.

  $\Rightarrow$ Enclosure must be "water tight" for effectively suppress pickup at high frequencies (> order 10 MHz).
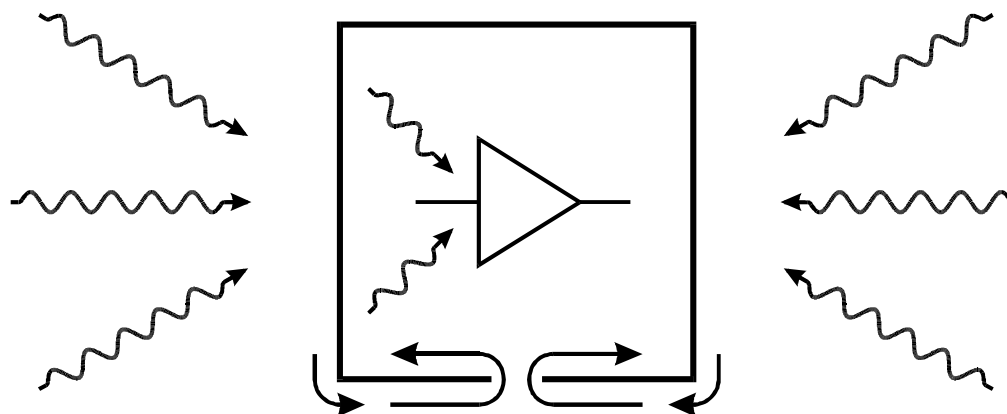
Example: RF-tight shielding of multi-channel sub-ns amplifier
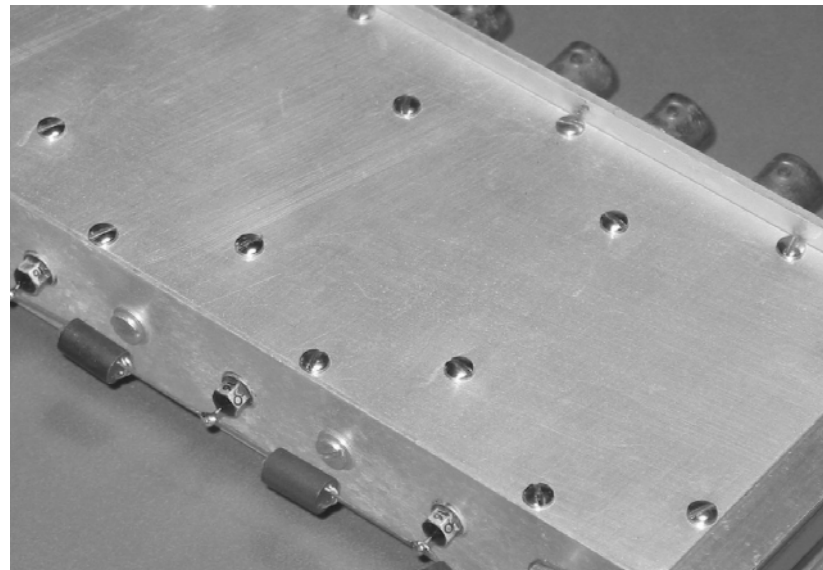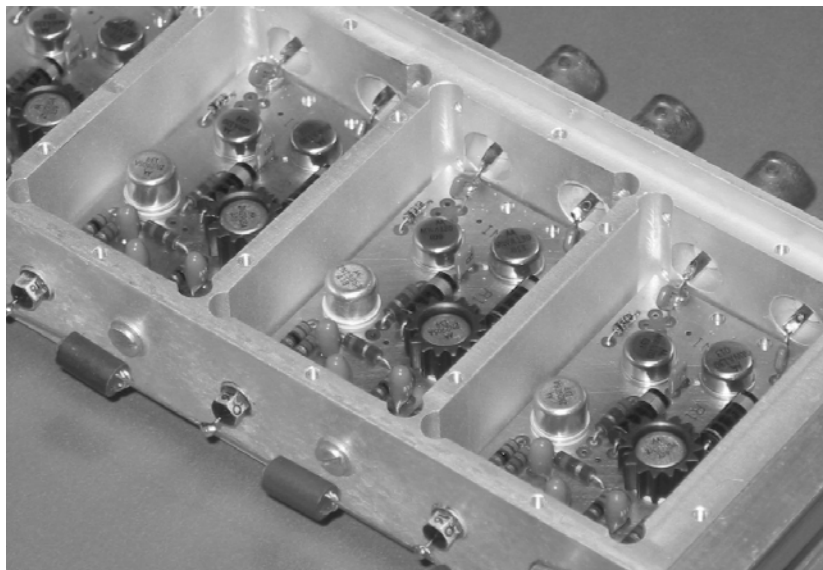
b) "Field Line Pinning"

Full shielding is not always practical, nor is it always necessary.

Rather than preventing interference currents from entering the detector system, it is often more practical to reduce the coupling of the interference to the critical nodes.

Consider a conductor carrying an undesired signal current, with a corresponding signal voltage. Capacitive coupling will transfer interference to another circuit node.

If an intermediate conductor is introduced with a large capacitance to the interference source and to ground compared to the critical node, it will "capture" the field lines and effectively "shield" the critical node.
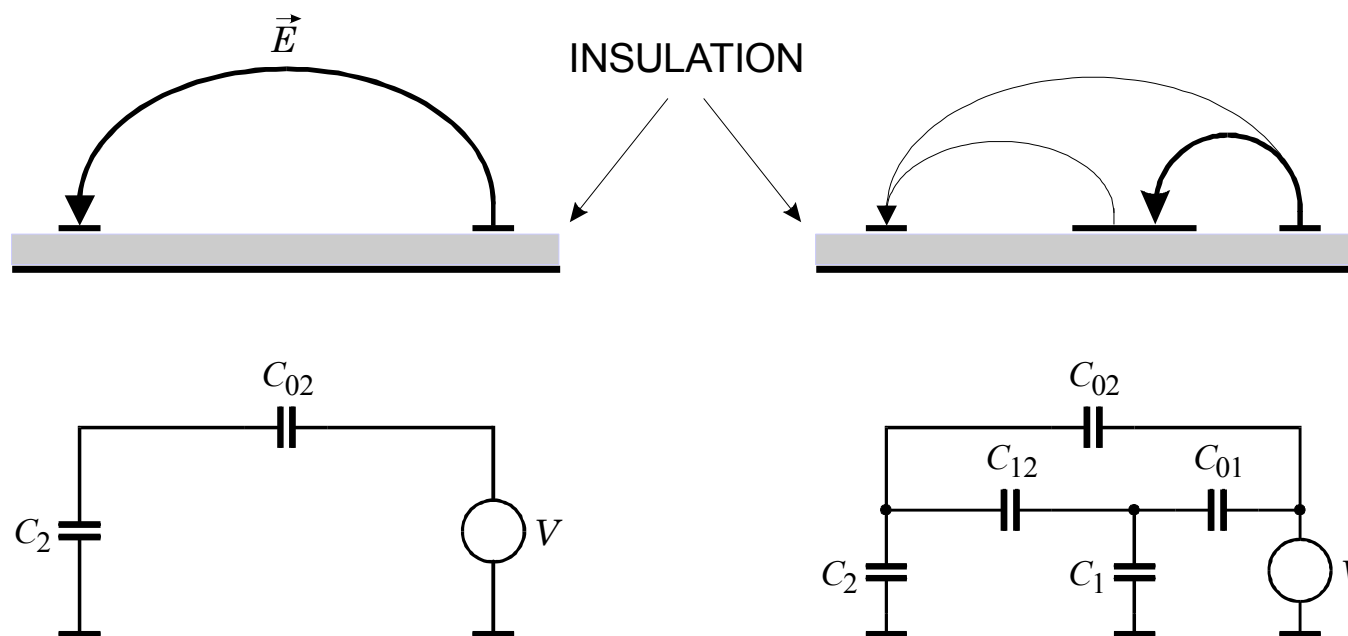
c) "Self-Shielding" Structures

The magnitude of capacitive coupling depends on the dielectric constant of the intermediate medium.

1

$\varepsilon_r = 1$

Ensemble of electrodes:
$\varepsilon_r = 1$ in volume between
    set 2 to set 1 and
$\varepsilon_r > 1$ between sets 2 and 3.

2

$\varepsilon_r > 1$

3

The capacitance between electrode sets 2 and 3 is ε_r times larger than in sets 1 to 2.

Example: Si, $\varepsilon_r = 11.9 \Rightarrow$ 92.2% of the field lines originating from electrode set 2 terminate on set 3, i.e. are confined to the Si bulk 7.8% terminate on set 1.

For comparison, with $\varepsilon_r = 1$, 50% of the field lines originating from electrode set 2 terminate on set 1.

$\Rightarrow$ High dielectric constant reduces coupling of electrode sets 2 and 3 to external sources.

If the interference source is represented by electrode set 1 and sets 2 and 3 represent a detector
    $\Rightarrow$ Si detector is 6.5 times less sensitive to capacitive pickup then a detector with $\varepsilon_r = 1$ (e.g. a gas chamber with the same geometry)

d) "Self-Shielding" Cables

In mixed analog-digital systems, interfering signals may radiate from cables, especially digital transmission lines.

By utilizing broadside-coupled differential lines with a thin intermediate dielectric, the field is confined to the region between the conductors. The extent of the fringing field beyond the conductor edge is about equal to the thickness of the dielectric.
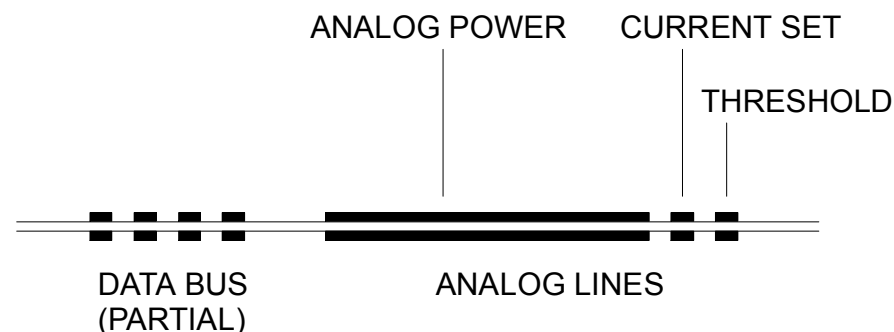
Example:

Conductors (data): 50 μm thick,
150 μm wide

Dielectric: 50 μm thick

Gap between pairs: 150 μm

Cross-coupling between adjacent pairs:
< 2% at 60 MHz for 1 m length

ANALOG POWER   CURRENT SET

THRESHOLD

DATA BUS
(PARTIAL)   ANALOG LINES

Power connections are made substantially wider (1 – 5 mm), forming a low impedance transmission line with high distributed capacitance.

The geometry shown above is for short runs in the inner region of a tracker, where reduction of material is crucial. Dimensions can be scaled proportionally to achieve lower resistance and signal dispersion in longer cable runs at larger radii.

4. Inductive Coupling

A varying B field induces voltages in circuit loops.

$$\frac{\partial B}{\partial t}$$

$$V_{ind} = -A\frac{\partial B}{\partial t}$$

DET
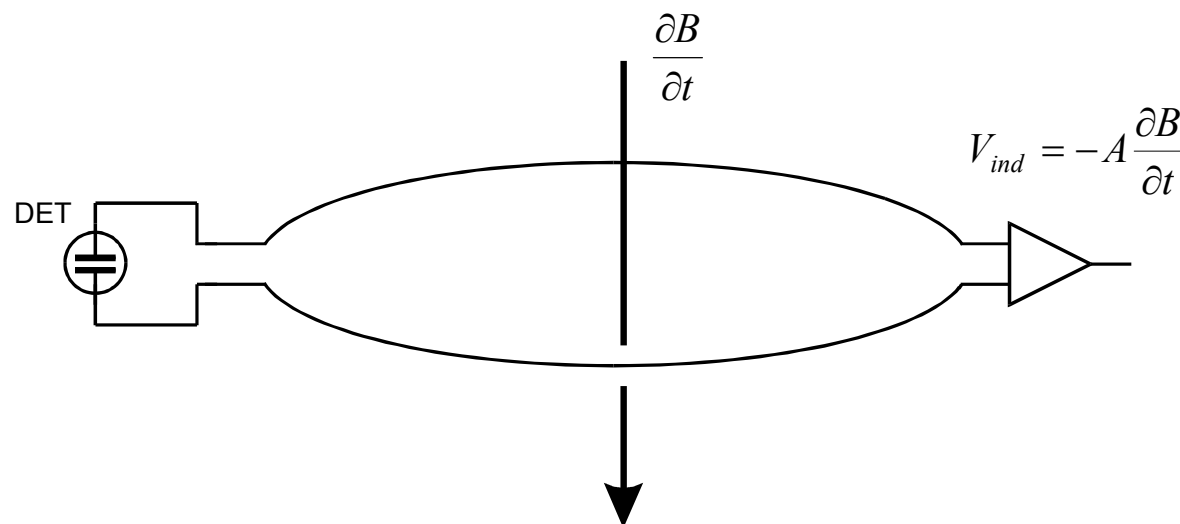
Clearly, the area A enclosed by any loops should be minimized.

Accomplished by routing signal line and return as a closely spaced pair.

Better yet is a twisted pair, where the voltages induced in successive twists cancel.

Problems occur when alternating detector electrodes are read out at opposite ends – often done because of mechanical constraints.

5. 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.
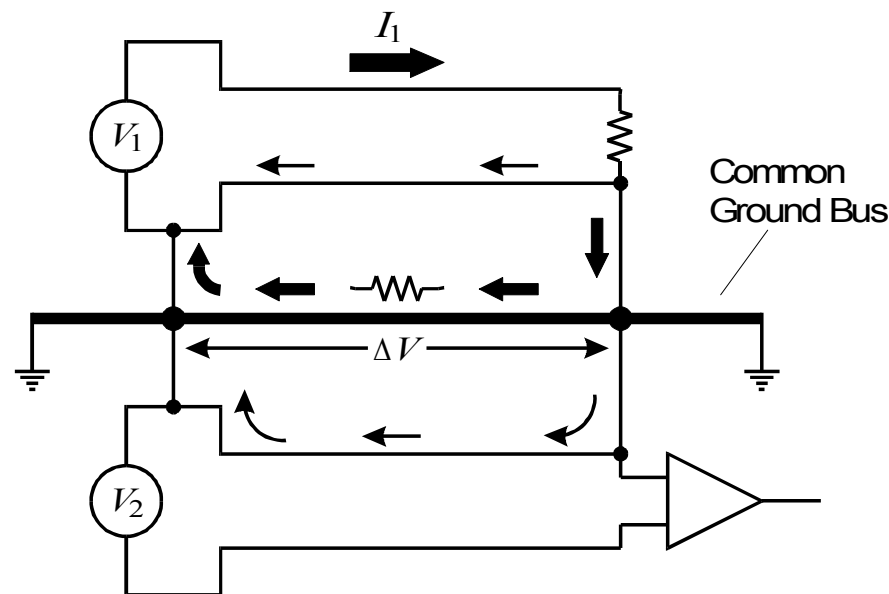
- Cross-coupling has *nothing to do with grounding per se*, but is due to the common return path. However, the common ground caused the problem by establishing the shared path.

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.
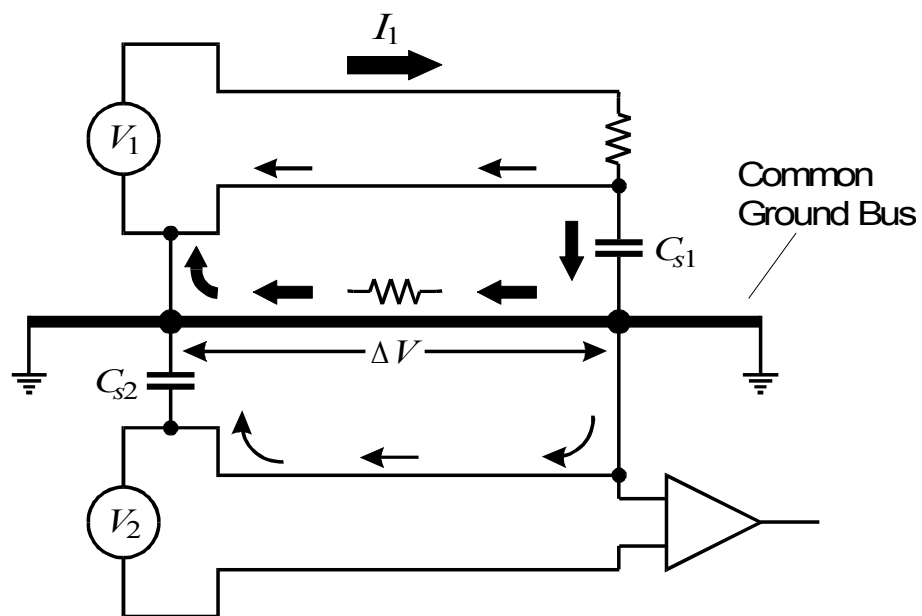
The loops in this figure are the same as shown before, but the loops are closed by the capacitances C_{s1} and C_{s2}.

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.
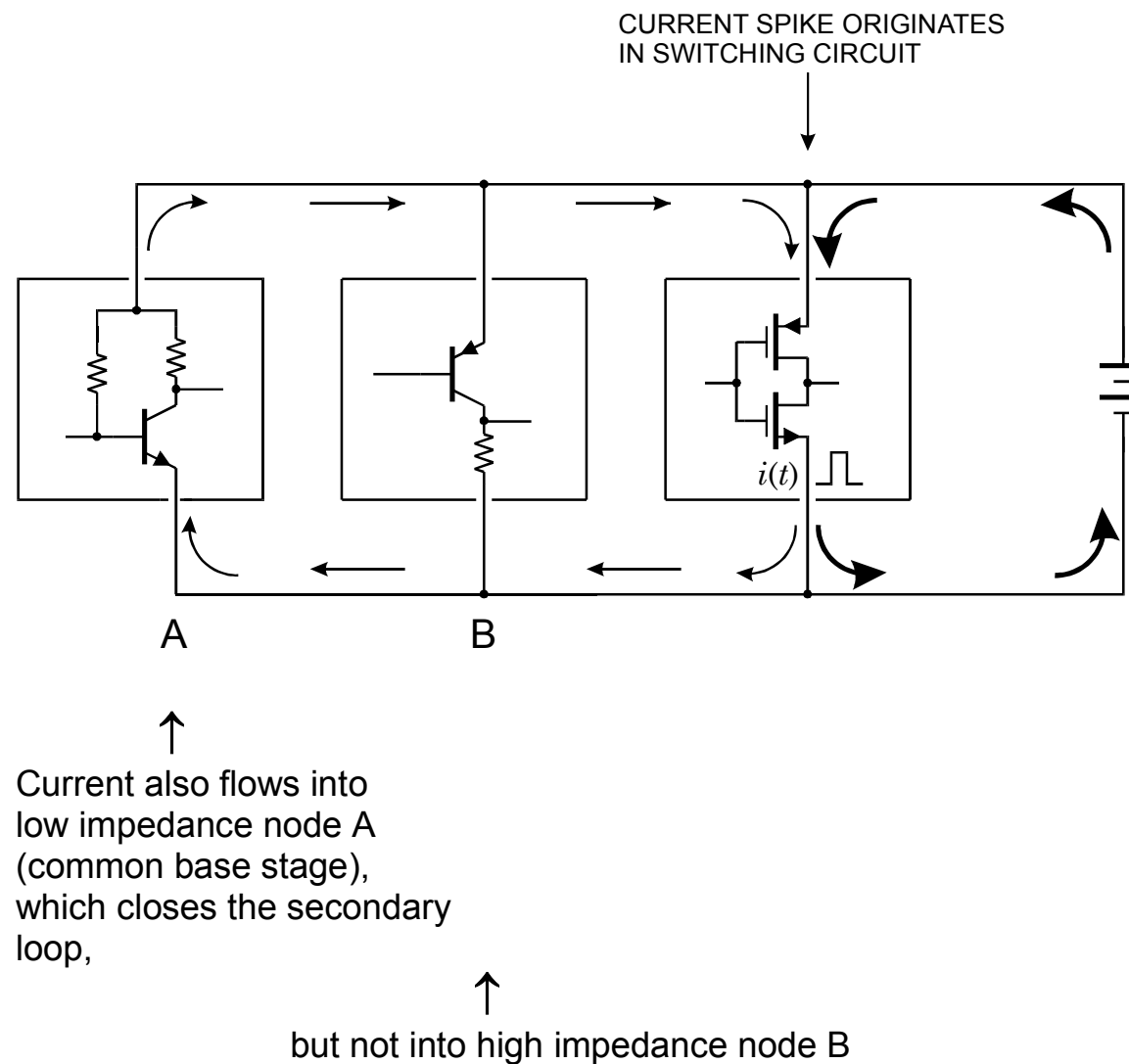
For AC signals the inductance of the common current path can increase the impedance substantially beyond the DC resistance, especially at high frequencies.

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

Interference does not cross-couple by voltage alone, but also via current injection.

Current spikes
originating in logic
circuitry, for example,
propagate through
the bussing system
as on a transmission
line.

Individual connection
points will absorb
some fraction of the
current signal,
depending on the
relative impedance of
the node.

CURRENT SPIKE ORIGINATES
IN SWITCHING CIRCUIT

$i(t)$

A   B

Current also flows into
low impedance node A
(common base stage),
which closes the secondary
loop,

but not into high impedance node B

Remedial Techniques

1. Reduce impedance of the common path

    $\Rightarrow$ 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 $\Rightarrow$ continual surprises

2. Avoid Grounds

Circuits rely on current return paths, not a ground connection!
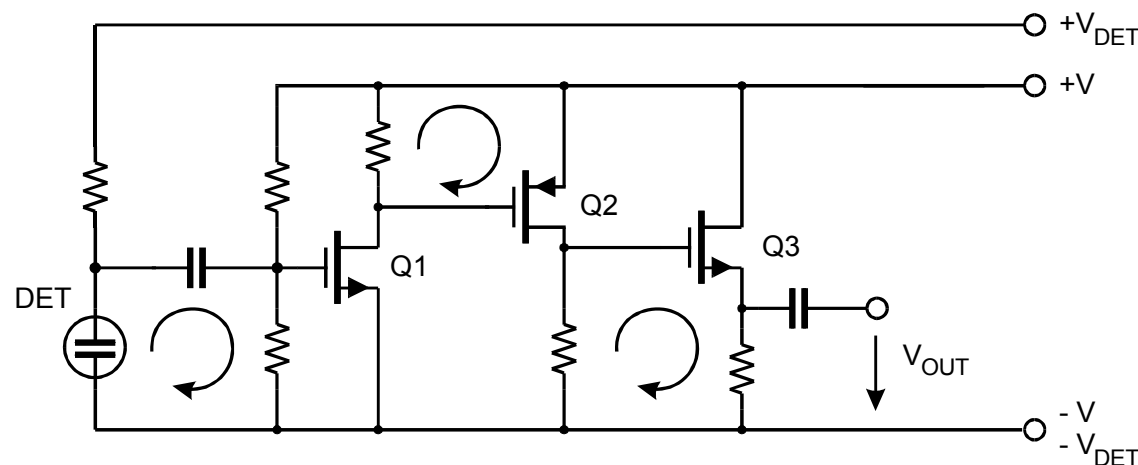
In transferring from stage to stage the signal current flows through local return loops.

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.

MAIN AMP.

BIAS SUPPLY

PREAMPLIFIER

INSULATED FEEDTHROUGH

DET. BOX
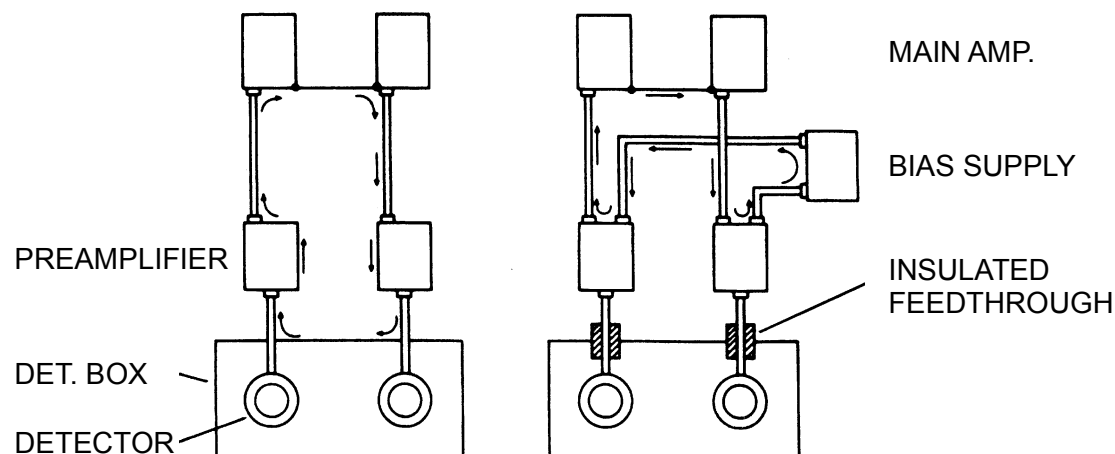
DETECTOR

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:
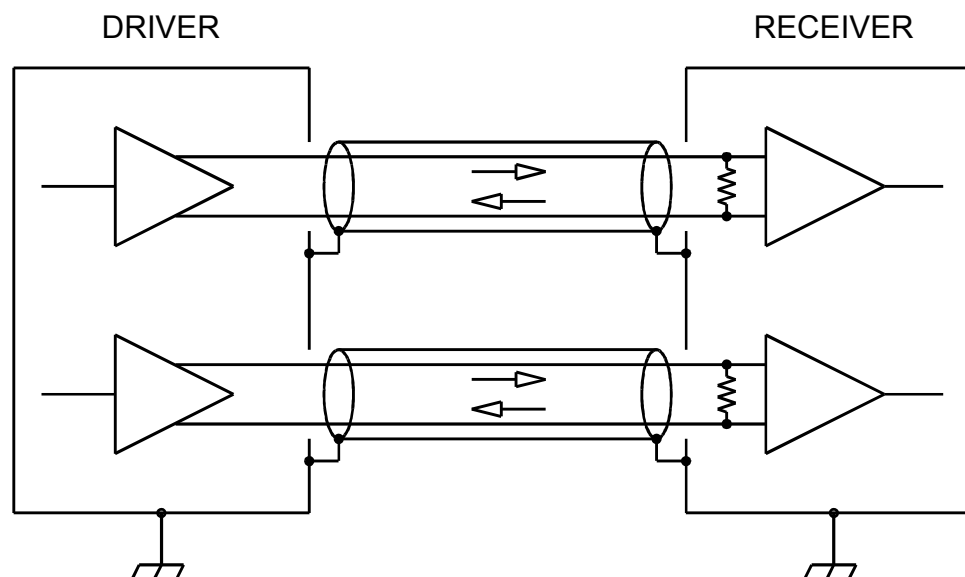
Technique also usable with single-ended drivers:
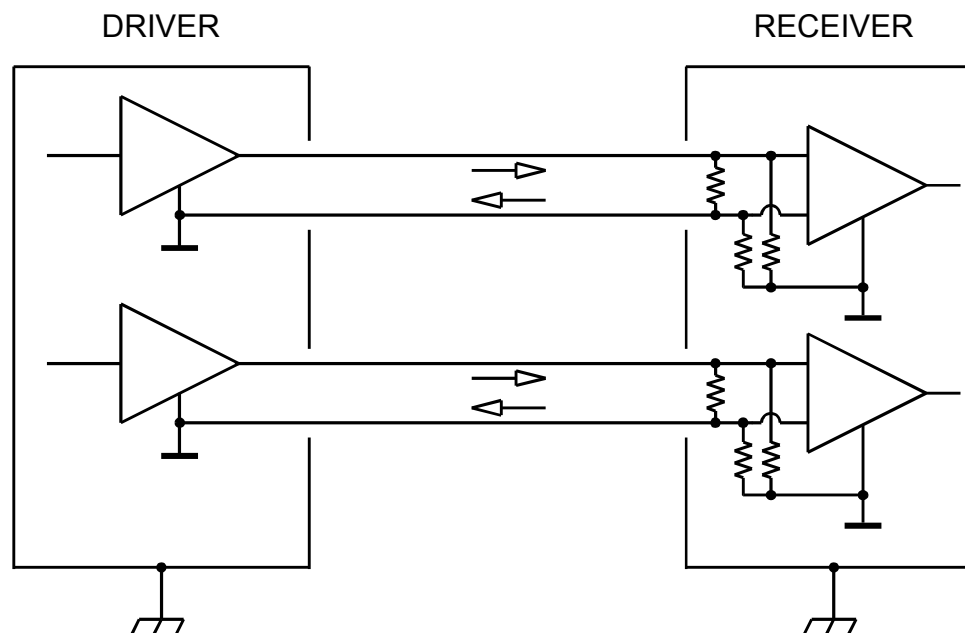
At the receiver input high-value resistors to ground provide potential referencing between the transmitter and receiver to avoid exceeding the common mode range of the receiver.
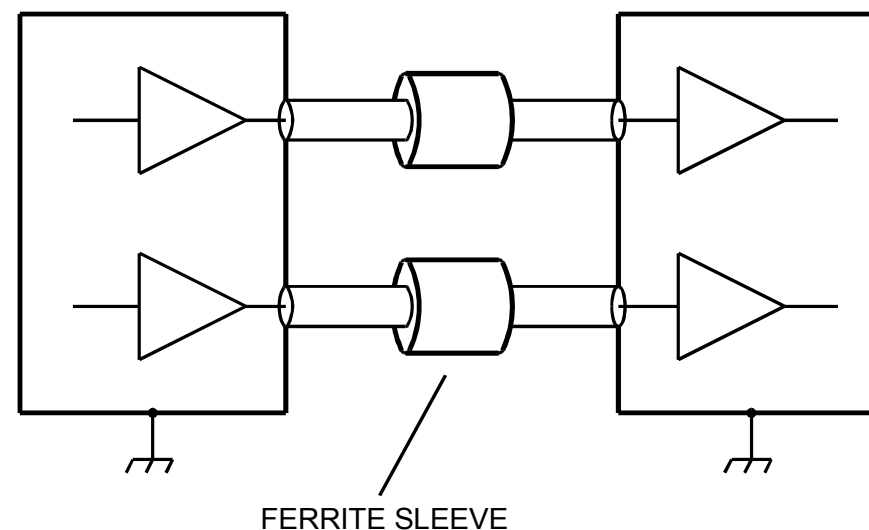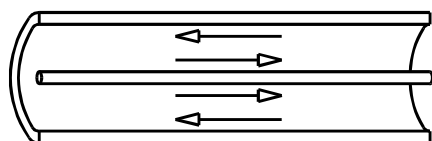
The transmission line is terminated by the shunt resistor (typ. 100 Ω)

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.

FERRITE SLEEVE

Net field at *outer surface* of shield is zero. $\Rightarrow$　　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.

DETECTOR   PREAMPLIFIER   SHAPER

R_2

R_1 C_1

C_2

R_3

ISOLATION
RESISTORS

DETECTOR
BIAS
SUPPLY

COAX SHIELD INSULATED
FROM LOCAL GROUND
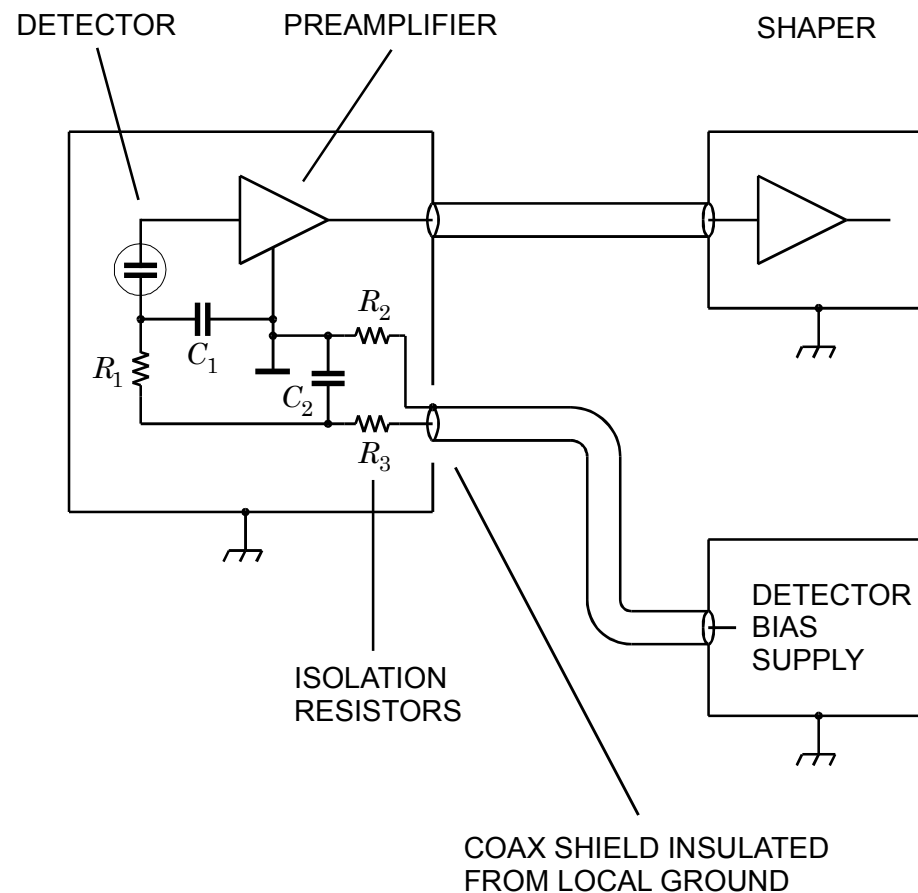
"Ground loops" are often formed by the third wire in the AC power connection. Avoid voltage differences in the "ground" connection by connecting all power cords associated with low-level circuitry into the same outlet strip.

3. Direct the current flow away from sensitive nodes

A timing discriminator was built on a PC board and mounted in a NIM module with multiple channels.

All inputs and outputs were mounted on the front panel. The outputs drove about 20 mA into 50 Ω cables.

Whenever an output fired, the unit broke into oscillation.
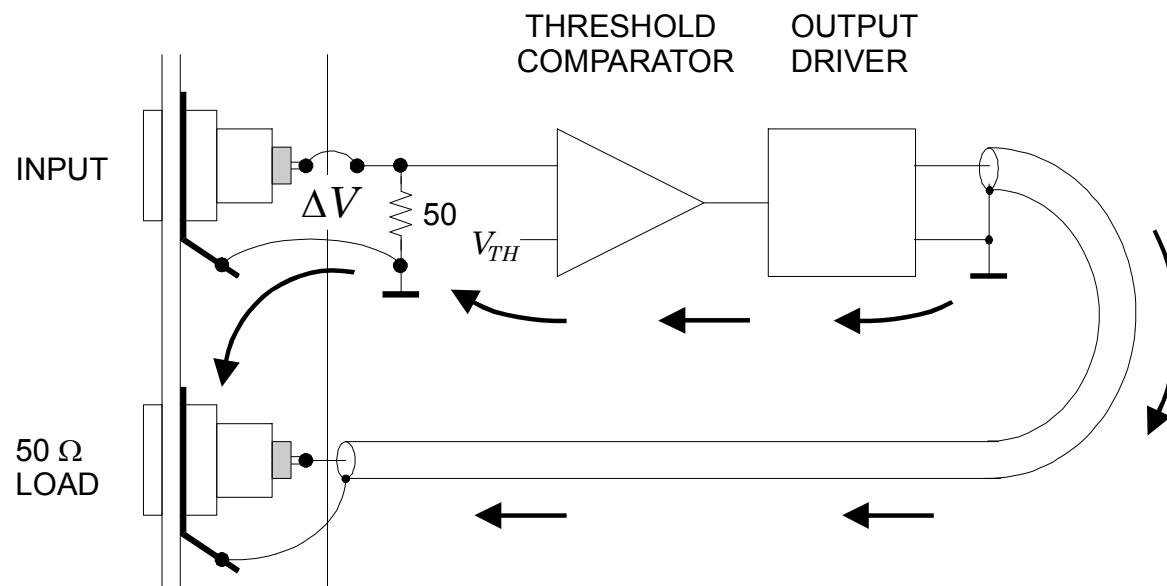
A portion of the output current flowed through the input ground connection. The voltage drop ΔV was sufficient to fire the comparator.
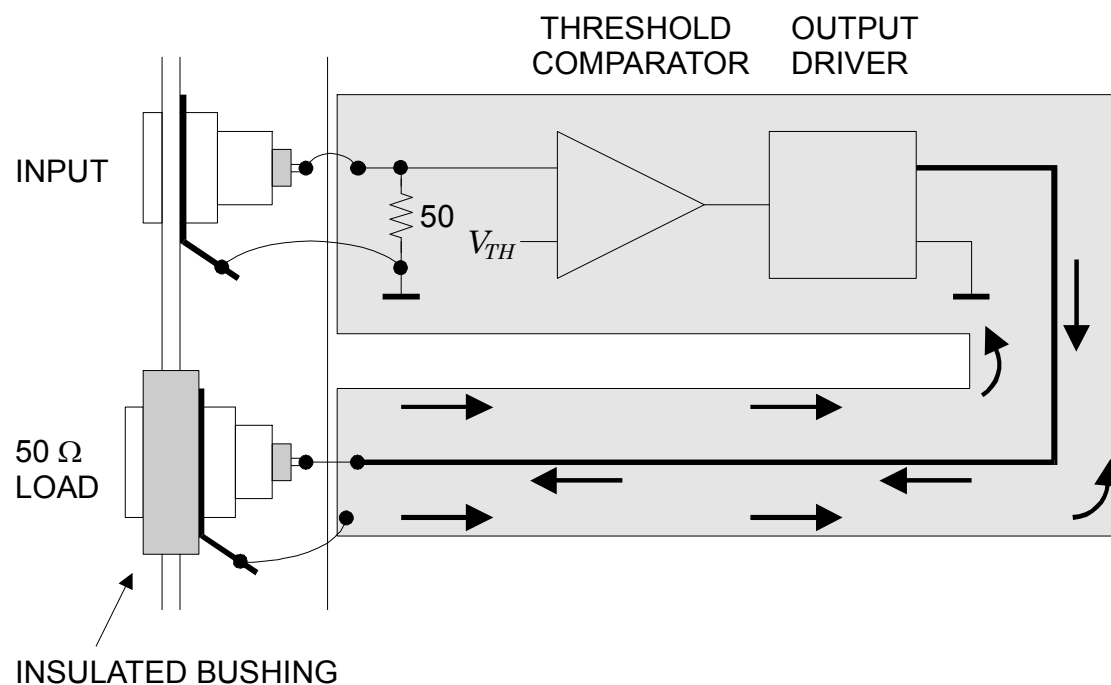
Breaking the loop by insulating the output connector from the front panel fixed the problem.
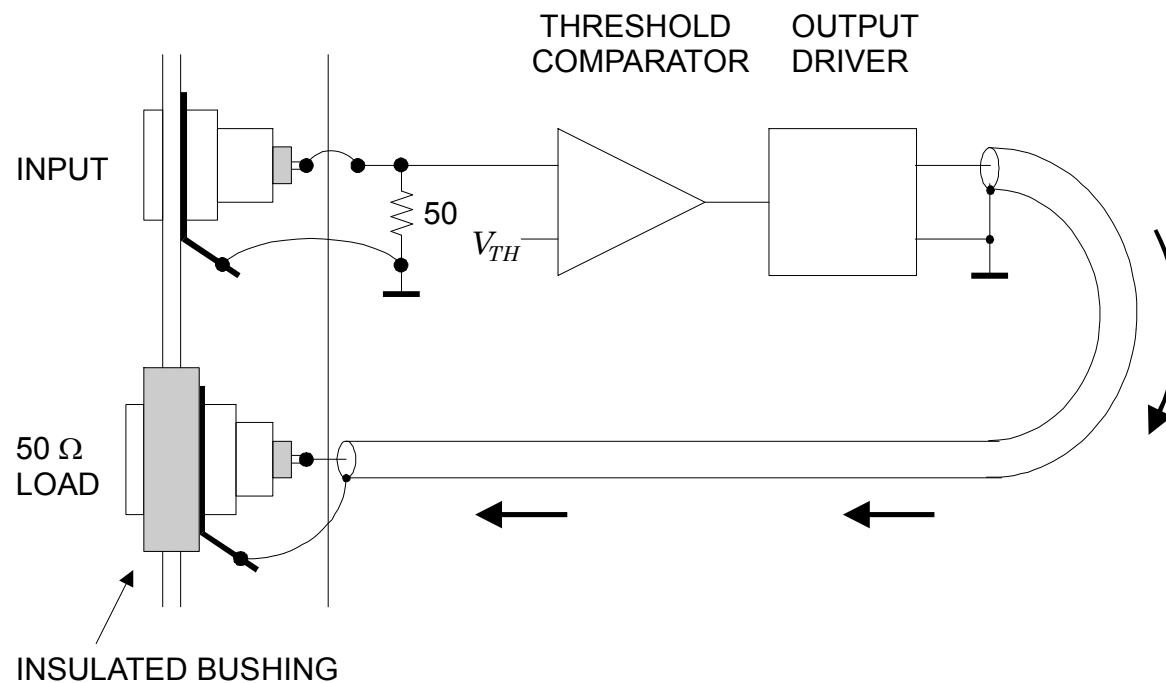
Often it is convenient to replace the coax cable at the output by a microstrip line integrated on the PC board.

Signal Trace
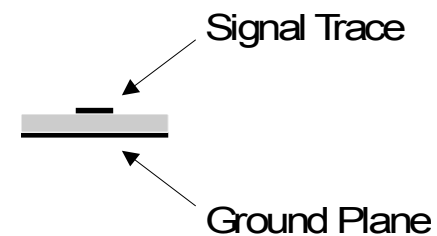
Ground Plane

Current paths can be controlled by patterning the ground plane.

THRESHOLD COMPARATOR   OUTPUT DRIVER

INPUT

50

V_{TH}

50 Ω LOAD

INSULATED BUSHING

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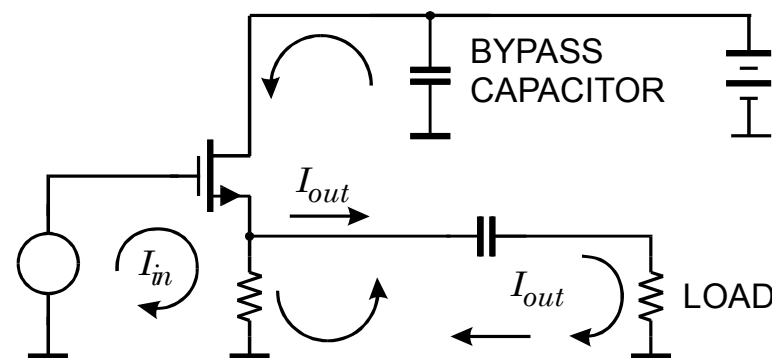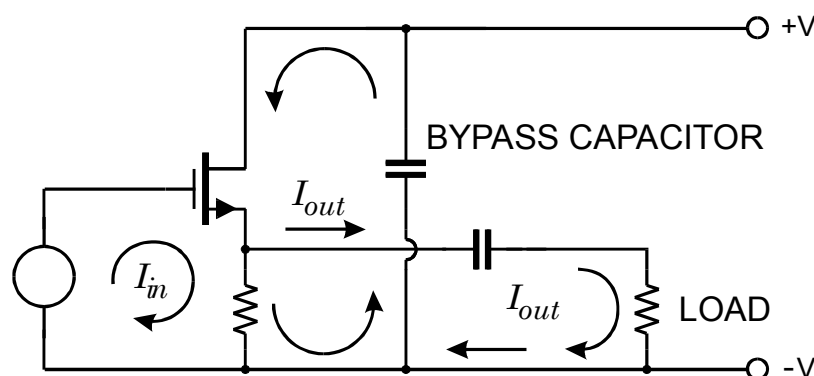
Since the "ground" is a large area conducting surface – often a chassis or a ground plane – with a "low" impedance, it is considered to be an equipotential surface.

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!

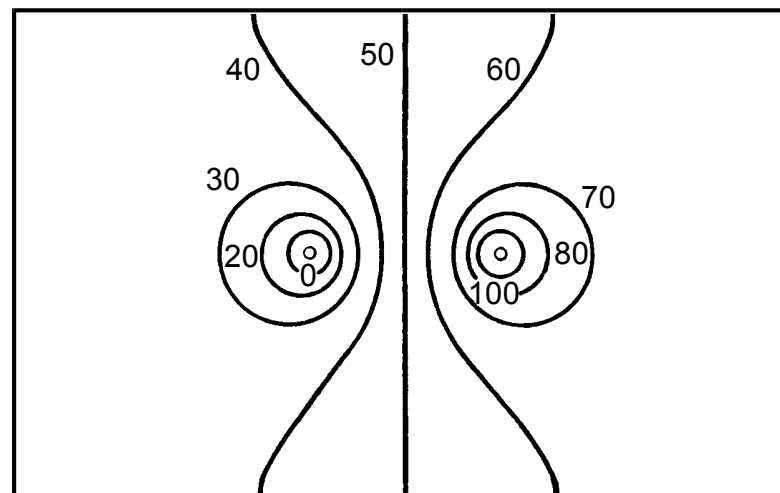Consider a current loop closed by two connections to a ground plane.

Current distribution around the two connection points
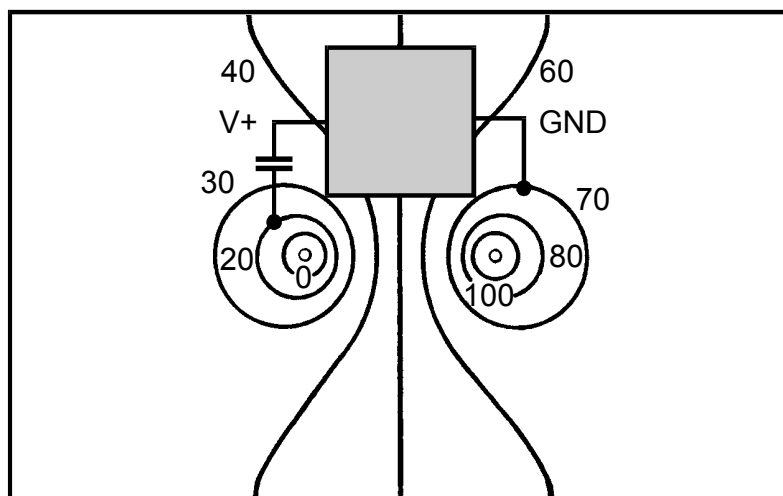
The dashed lines indicate equipotential contours.
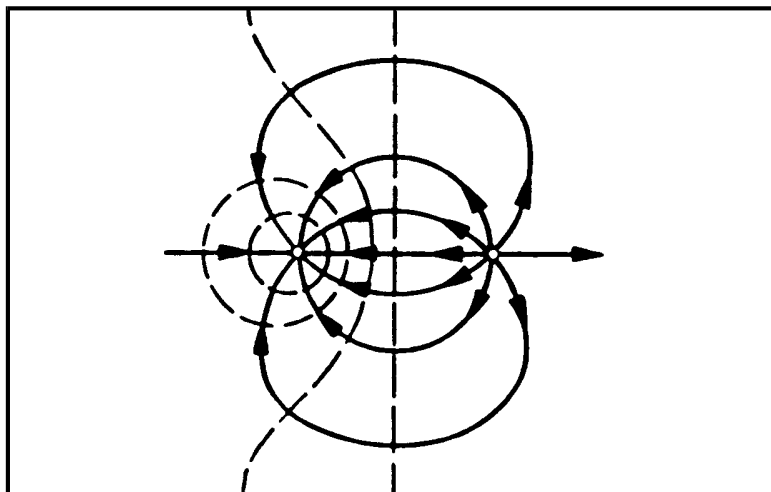
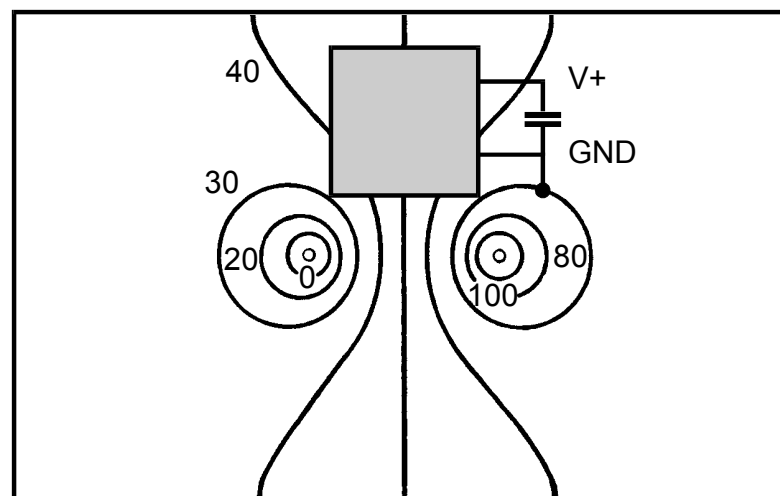Assume a total drop of 100 mV.

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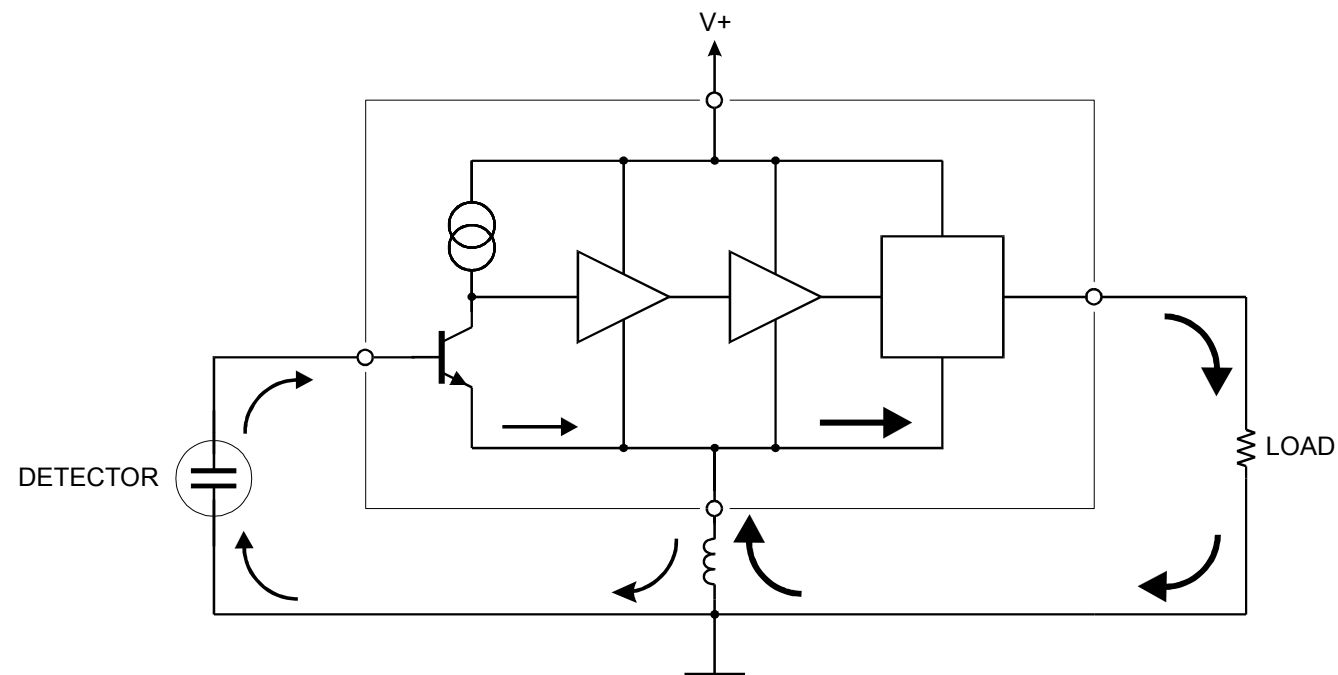
Direct connection of the bypass capacitor between the V+ and GND pads avoids pickup of the voltage drop on the ground plane.

"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.
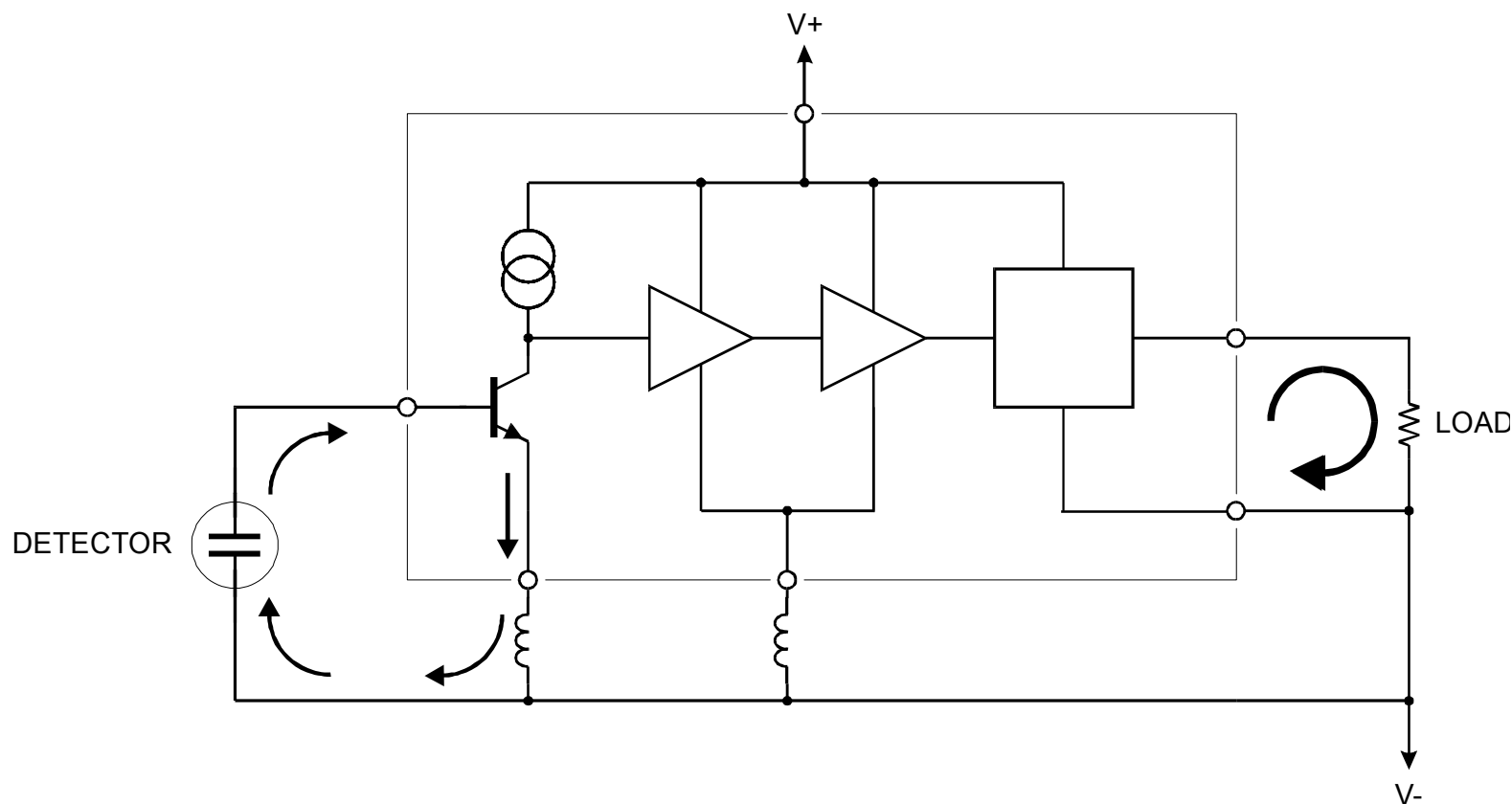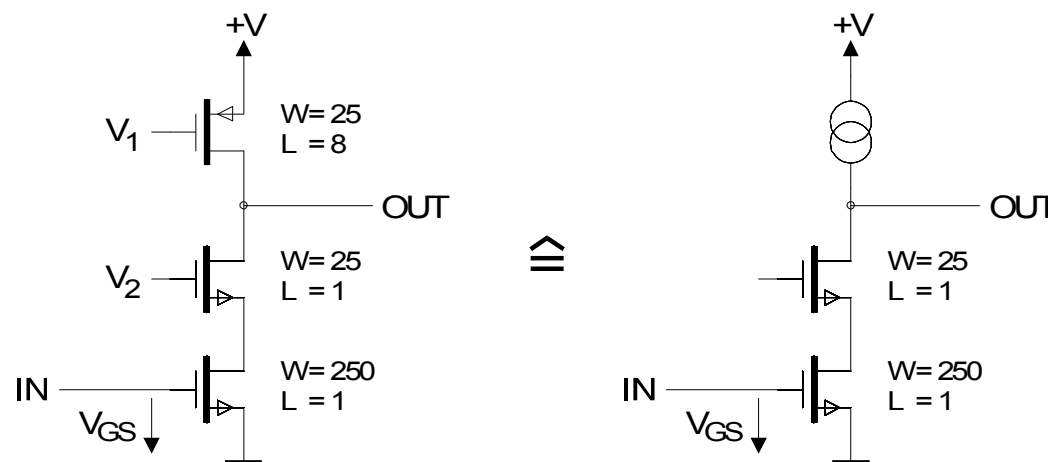
The Folded Cascode

The folded cascode is frequently used in preamplifiers optimized for low power.

Standard cascode with representative transistor sizes:

The cascode combines two transistors to obtain

- the high transconductance and low noise of a wide transistor

- the high output resistance (increased by local feedback) and small output capacitance of a narrow transistor

- reduced capacitance between output and input

Since the input transistor determines the noise level, its current requirement tends to dominate.

In a conventional cascode the current required for the input transistor must flow through the whole chain.

The folded cascode allows the (second) cascode transistor to operate at a lower current and, as a result, higher output resistance.

PMOS transistors tend to have lower "1/f" noise than NMOS devices, so this adaptation is often used:
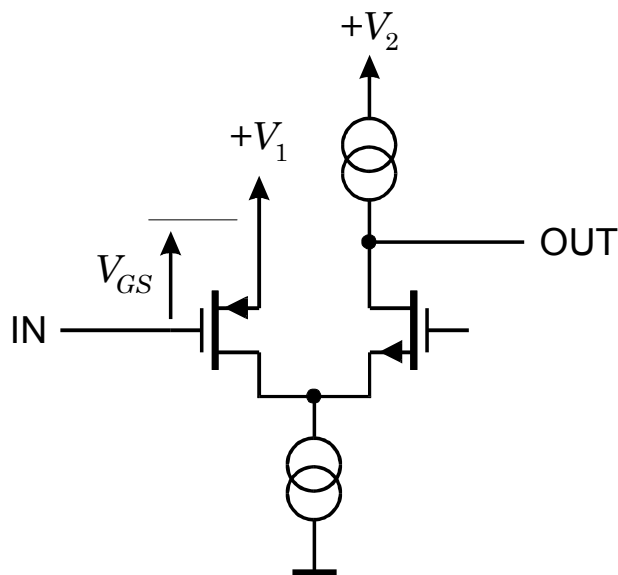

The problem with this configuration is that the supply V_1 becomes part of the input signal path. Unless the V_1 supply bus is very carefully configured and kept free of other signals, interference will be coupled into the input.

Consider the circuit connected to a strip detector:
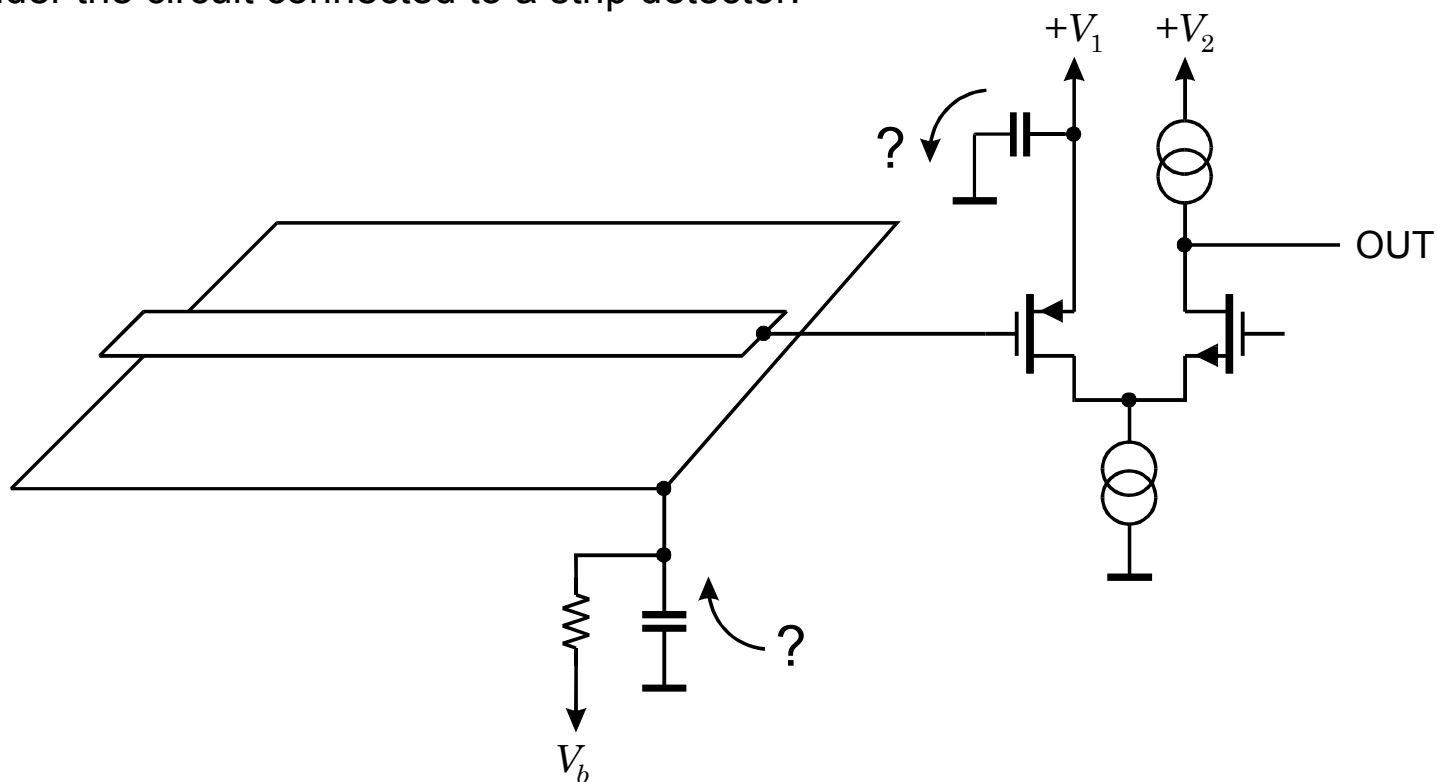
Unless the connection points of the bypass capacitors from the FET source and the detector backplane are chosen carefully, interference will be introduced into the input signal loop.
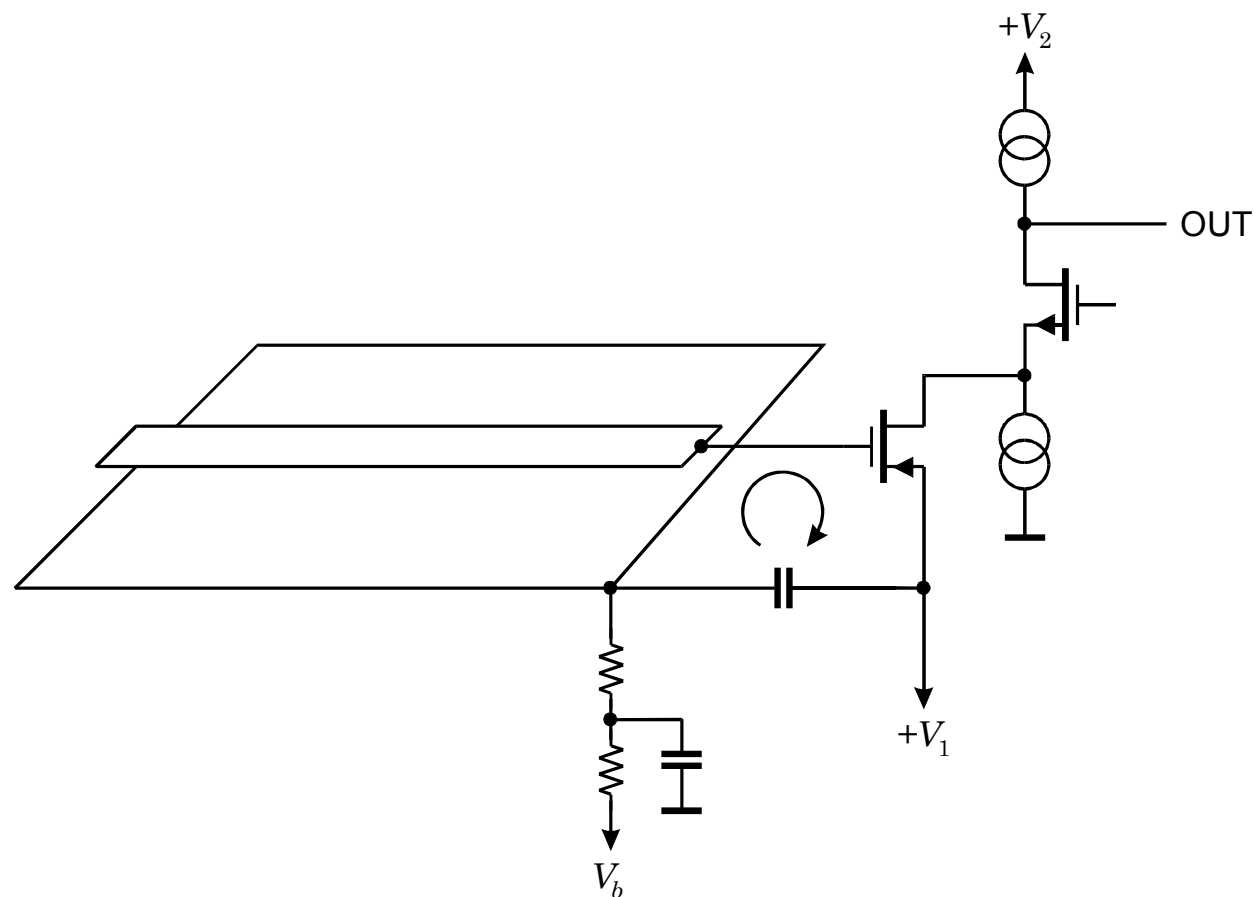
It is much better to "ground" the FET source to a local signal reference and use a negative second supply.
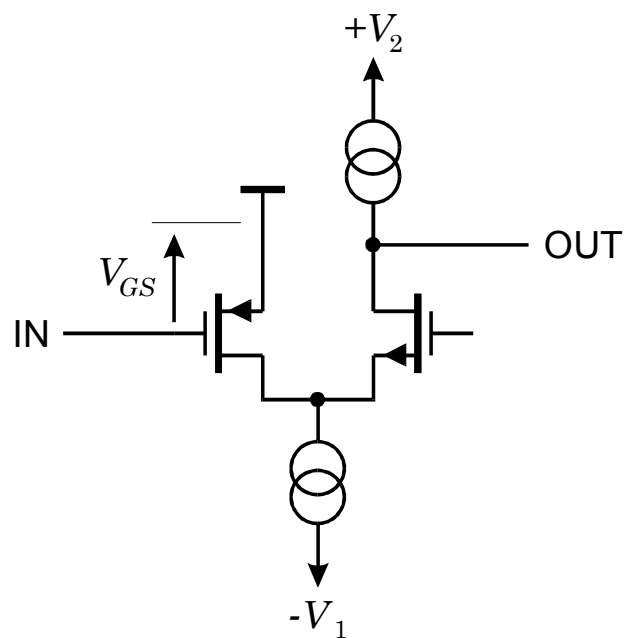
Connected to a strip detector (and redrawn slightly), this configuration provides a direct input return loop.
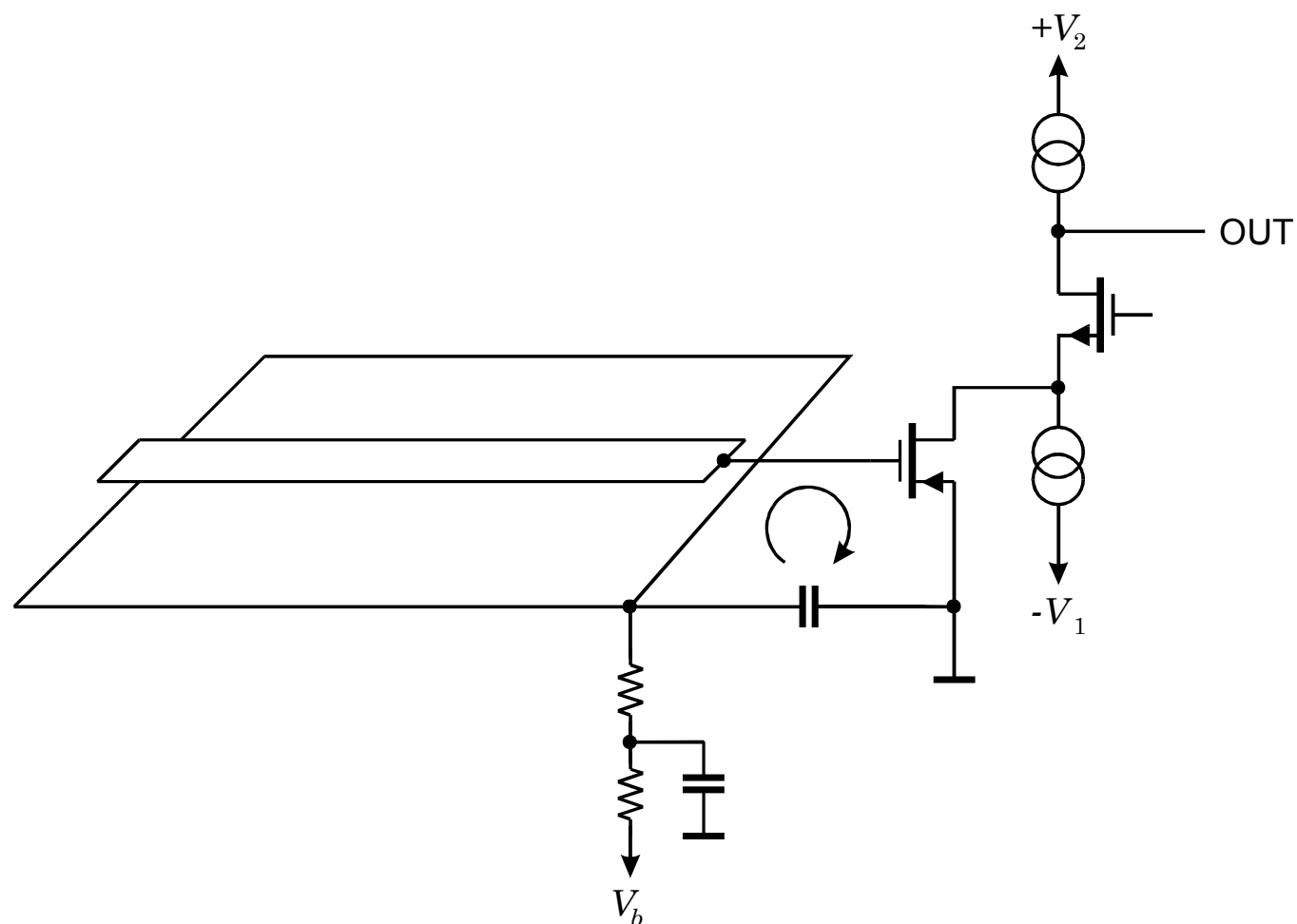
For some (mythical?) reason positive supplies are more popular.
Proper connection of the detector can still provide a direct input path.

$+V_2$

OUT

$+V_1$

V_b

In most implementations supply lines are more susceptible to pickup, so the $+V_1$ line must be properly filtered to prevent current injection.
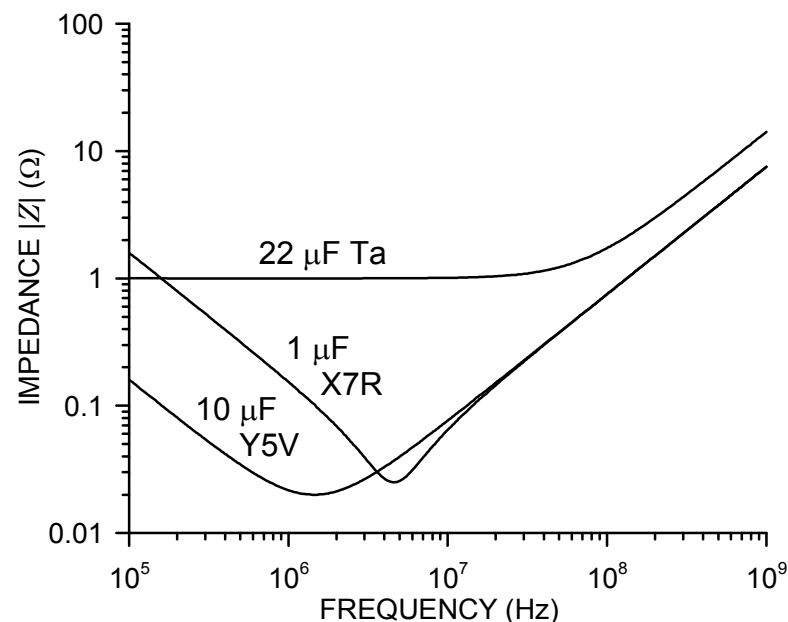
Choice of Capacitors

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
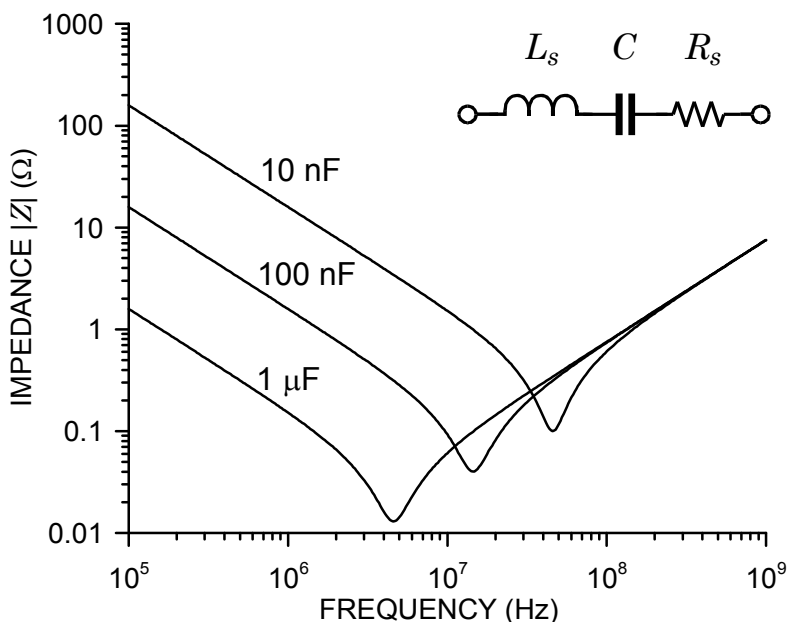
Comparison between X7R, Y5V ceramic and Tantalum chip capacitors.

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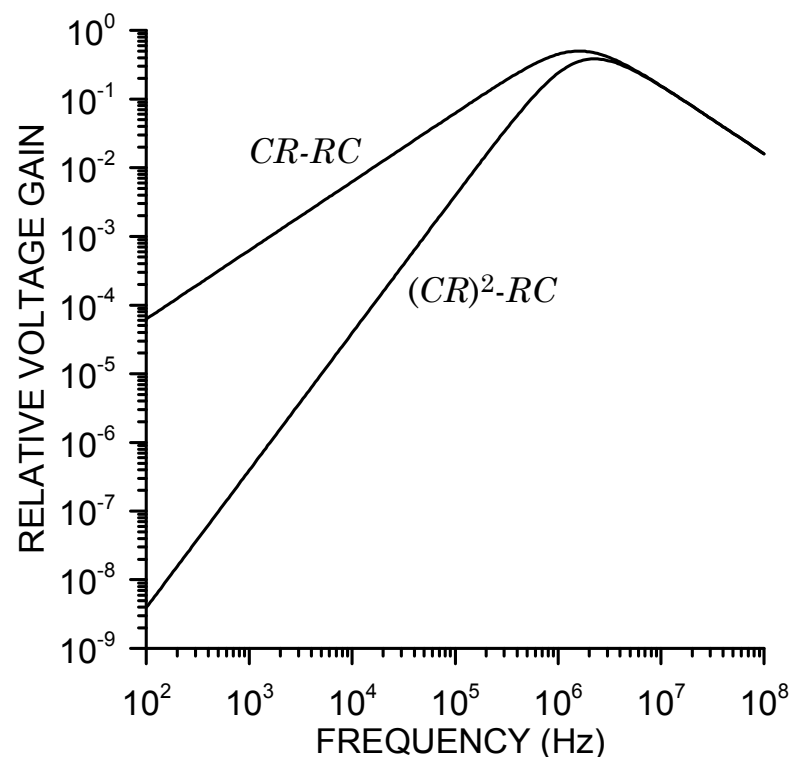
Other Considerations

1. Choice of Shaper

Although a bipolar shaper has slightly inferior noise performance than a unipolar shaper, it may provide better results in the presence of significant low-frequency noise.

Minimum Noise

CR-RC $\qquad Q_{n,opt} = 1.355 \sqrt{i_n e_n C}$

$(CR)^2$-RC $\quad Q_{n,opt} = 1.406 \sqrt{i_n e_n C}$

In the frequency domain the additional CR-stage (low-pass filter) provides substantial attenuation of low-frequency interference.

2. Local Referencing

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

$\Rightarrow$ 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 rational for "grounding", but think of the physical mechanisms before blindly following recipes.

SUPPORT /
COOLING STAVE

DETECTOR

SIGNAL OUTPUT

DETECTOR BIAS

ISOLATION
RESISTORS

DETECTOR

SIGNAL OUTPUT

DETECTOR BIAS

ISOLATION
RESISTORS